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Revision 0

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Phenomena Identification and Ranking Tables (PIRT) for Un-Buffered/Buffered Boric Acid Mixing/Transport and Precipitation Modes in a Reactor Vessel During Post-LOCA Conditions

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Phenomena Identification and Ranking Tables (PIRT) for Un-Buffered/Buffered Boric Acid Mixing/Transport and Precipitation Modes in a Reactor Vessel During Post-LOCA Conditions

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*Electronically approved records are authenticated in the electronic document management system.

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Entergy	Palisades (CE)	X	
Entergy Nuclear Northeast	Indian Point 2 & 3 (W)	X	
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Florida Power & Light Group	St. Lucie 1 & 2 (CE)	X	
Florida Power & Light Group	Turkey Point 3 & 4, Seabrook (W)	X	
Florida Power & Light Group	Pt. Beach 1 & 2 (W)	X	
Luminant Power	Comanche Peak 1 & 2 (W)	X	
Omaha Public Power District	Fort Calhoun (CE)	X	
Pacific Gas & Electric	Diablo Canyon 1 & 2 (W)	X	
Progress Energy	Robinson 2, Shearon Harris (W), Crystal River 3 (B&W)	X	
PSEG – Nuclear	Salem 1 & 2 (W)	X	
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Tennessee Valley Authority	Sequoyah 1 & 2, Watts Bar (W)	X	
Wolf Creek Nuclear Operating Co.	Wolf Creek (W)	X	
British Energy	Sizewell B	X	
Electrabel (Belgian Utilities)	Doel 1, 2 & 4, Tihange 1 & 3	X	
Hokkaido	Tomari 1 & 2 (MHI)	X	
Japan Atomic Power Company	Tsuruga 2 (MHI)	X	
Kansai Electric Co., LTD	Mihama 1, 2 & 3, Ohi 1, 2, 3 & 4, Takahama 1, 2, 3 & 4 (W & MHI)	X	
Korea Hydro & Nuclear Power Corp.	Kori 1, 2, 3 & 4 Yonggwang 1 & 2 (W)	X	
Korea Hydro & Nuclear Power Corp.	Yonggwang 3, 4, 5 & 6 Ulchin 3, 4 , 5 & 6 (CE)	X	
Kyushu	Genkai 1, 2, 3 & 4, Sendai 1 & 2 (MHI)	X	
Nuklearna Electrarna KRSKO	Krsko (W)	X	
Nordostschweizerische Kraftwerke AG (NOK)	Beznau 1 & 2 (W)	X	
Ringhals AB	Ringhals 2, 3 & 4 (W)	X	
Shikoku	Ikata 1, 2 & 3 (MHI)	X	
Spanish Utilities	Asco 1 & 2, Vandellos 2, Almaraz 1 & 2 (W)	X	
Taiwan Power Co.	Maanshan 1 & 2 (W)	X	
Electricite de France	54 Units	X	

* This is a list of participants in this project as of the date the final deliverable was completed. On occasion, additional members will join a project. Please contact the PWR Owners Group Program Management Office to verify participation before sending documents to participants not listed above.

ACKNOWLEDGEMENTS

We hereby acknowledge the participation and co-operation of the many internal and external expert reviewers cited in this report. Their patience, insight, and commitment to the understanding of the very technical aspects of mixing/transport and precipitation modes phenomena are greatly appreciated.

The authors would also like to thank Bob McFetridge (Westinghouse) for his leadership in conducting the PIRT strategy meeting for addressing boric acid buffering agents and low levels of sump debris. The authors would also like to thank Kyle Shearer (Westinghouse) for his contributions in putting this report together.

Finally, a very special acknowledgement is made to the late Dr. Lawrence E. Hochreiter who made significant contributions to the report; to the nuclear industry; and countless engineering students. Dr. Hochreiter was a great friend and teacher who will be greatly missed.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACRS	Advisory Committee of Reactor Safeguards
ACS	American Chemical Society
AOR	Analysis of Record
APS	American Physical Society
B&W	Babcock and Wilcox
BACCHUS	Mitsubishi Heavy Industries Boric Acid Concentration Core Mixing Tests
BAMT	Boric Acid Makeup Tank (typical CE plant terminology)
CCFL	Counter Current Flow Limitation
CE	Combustion Engineering
CEA	Control Element Assembly (typical CE plant terminology)
CENPD	CE Technical Report Number Preface
CFD	Computational Fluid Dynamics
CFX	Computational Fluid Dynamics Code
CLPD	Cold Leg Pump Discharge (Leg)
CLPS	Cold Leg Pump Suction (Leg)
ECCS	Emergency Core Cooling System
EOP(s)	Emergency Operating Procedure(s)
EPRI	Electric Power Research Institute
EPU	Extended Power Uprate
FLECHT	Full Length Emergency Core Heat Transfer (Tests)
LBLOCA	Large Break LOCA
LOCA	Loss-of-Coolant Accident
LPI	Low Pressure Injection
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
PIRT	Phenomena Identification and Ranking Table
PSU	Pennsylvania State University
PWR	Pressurized Water Reactor
PWROG	Pressurized Water Reactor Owners Group
PZR	Pressurizer
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RV	Reactor Vessel
RVVV	Reactor Vessel Vent Valves
RWST	Refueling Water Storage Tank (typical Westinghouse plant terminology)
SBLOCA	Small Break LOCA
SG	Steam Generator
SI	Safety Injection

SOK	State of Knowledge
UPI	Upper Plenum Injection
VVER	Vodo-Vodni Energiini Reqktor, also known as Water-Water Energy Reactor
WCAP	Westinghouse Technical Report Number Preface (formerly Westinghouse Commercial Atomic Power)
WOG	Westinghouse Owners Group (now PWR Owners Group)

1 EXECUTIVE SUMMARY

All three US Pressurized Water Reactor (PWR) designs (Westinghouse, CE, and B&W) use boron as a core reactivity control method and are subject to concerns regarding potential boric acid precipitation in the core for scenarios that preclude direct Safety Injection (SI) flow through the core for extended periods following a Loss-of-Coolant Accident (LOCA). All three plant designs have Emergency Core Cooling System (ECCS) features that include an active core dilution mechanism to prevent the core region boric acid concentration from reaching the precipitation point. The common approach for demonstrating adequate boric acid dilution in a post-LOCA scenario includes the use of simplified methods with conservative boundary conditions and assumptions. These simplified methods are used with limiting scenarios in calculations that determine the time at which appropriate operator action must be taken to initiate an active boric acid dilution flow path or alternately, to show that boric acid precipitation will not occur. Simplified methods require assumptions regarding mixing in the reactor vessel. These assumptions affect the calculated rate of boric acid build-up in the core and the potential for boric acid precipitation. It is common to use assumptions that credit complete mixing in some regions (i.e., core region), partial mixing in some regions (i.e., lower plenum), while ignoring the effect of mixing in other regions (i.e., hot leg piping).

Improved boric acid precipitation analysis methodologies require insights on the phenomena that affect transport and mixing in the reactor vessel after a LOCA. A Phenomena Identification and Ranking Table (PIRT) is useful in identifying and ranking such phenomena and can be used as guidance when developing new evaluation models. Specifically the PIRT can be used to provide a basis for developing analytical mixing models and can support scaled testing and plant evaluation model development.

Section 2 provides brief background information on boric acid precipitation analysis methodology issues for US PWRs. Section 3 provides information on Westinghouse, Combustion Engineering (CE), and Babcock and Wilcox (B&W) plant designs and typical boric acid precipitation analysis methodology. Sections 4 through 8 present the PIRT process, external and internal PIRT review experts, and rankings and rationale for precipitation modes and mixing/transport of un-buffered and buffered boric acid from expert review. Section 9 provides a high-level assessment of how containment sump debris and GSI-191 issues may impact the PIRT rankings. Section 10 presents the overall PIRT conclusions for the precipitation modes and mixing/transport of un-buffered and buffered boric acid within a reactor vessel. Section 11 makes recommendations for practical use of the PIRT and suggests future areas of focus.

2 INTRODUCTION

All three US PWR designs (Westinghouse, CE, and B&W) use boron as a core reactivity control method and are subject to concerns regarding potential boric acid precipitation in the core for scenarios that preclude direct SI flow through the core for extended periods following a LOCA. All three plant designs have ECCS features that include an active core dilution mechanism to prevent the core region boric acid concentration from reaching the precipitation point. These dilution mechanisms may or may not require operator action. The common approach for demonstrating adequate boric acid dilution in a post-LOCA scenario includes the use of simplified methods with conservative boundary conditions and assumptions. These simplified methods are used with limiting scenarios in calculations that determine the time at which appropriate operator action must be taken to initiate an active boric acid dilution flow path or alternately, to show that boric acid precipitation will not occur. The three US PWR designs have different ECCS designs, different procedures for preventing boric acid precipitation, and different methodologies for evaluating the potential for boric acid precipitation. Nevertheless, there are common approaches, assumptions and simplifications that have been used in virtually all PWR calculations that address the potential for boric acid precipitation. Recent Extended Power Uprates (EPUs) have provided the opportunity for the Nuclear Regulatory Commission (NRC) to challenge some of these common approaches, assumptions and simplifications with regard to regulatory compliance and technical justification. In November 2005, the NRC issued a letter (Section 8, Reference 1) to the Westinghouse Owners Group (WOG, now Pressurized Water Reactor Owners Group (PWROG)) requesting that the PWROG members confirm that they have sufficient safety margin to core cooling requirements to support continued operation. The PWROG responded to the NRC in Reference 8-2. In Section 8, Reference 1, the NRC also asked that future methodologies justify the mixing assumptions used in predicting the build-up of boric acid in the reactor vessel after a LOCA. Throughout the US PWR fleet, it is common to find boric acid precipitation Analysis of Record (AOR) calculations that use simplifying assumptions regarding mixing in the reactor vessel after a LOCA. Such assumptions have typically credited complete mixing in some regions (i.e., core region), partial mixing in other regions (i.e., lower plenum), while ignoring the effect of mixing in other regions (i.e., hot leg piping).

3 BACKGROUND ON POST-LOCA BORIC ACID PRECIPITATION ANALYSIS METHODOLOGY

For typical plant designs (Westinghouse 2-loop Upper Plenum Injection (UPI) plants excluded), the limiting scenario for boric acid precipitation is a large cold leg (pump discharge) break where the downcomer is eventually filled and the excess SI flows out the break. The SI flow into the core region is largely limited to that quantity boiled off in the core to remove the decay heat. The steam generated in the core travels around the intact hot leg(s) (or through the internals Reactor Vessel Vent Valves (RVVVs) in the B&W-designed plants) to exit the break. Boric acid left behind accumulates in the core region and the boric acid concentration in the core region increases. The calculated rate of increase in boric acid concentration in the core region after a LOCA is directly affected by the assumed liquid volume. During this time, the core and upper plenum are filled with a two-phase mixture whose liquid content is dependent on the degree of voiding in the core and upper plenum region. The degree of voiding is a function of the core decay heat and Reactor Coolant System (RCS) pressure, and the pressure drop around the loop (or through the RVVVs) as it affects the hydrostatic balance between the downcomer head and the collapsed liquid level in the core. At low RCS pressures and high decay heat levels, the boiling in the core is vigorous, and the volume of liquid in the core region is smaller. As the decay heat drops off, the boiling becomes less vigorous and more liquid is retained in the core region.

Westinghouse US 2-loop plants differ from typical PWR designs in that they utilize low pressure upper plenum safety injection (or UPI). For these plants, the limiting large break LOCA boric acid precipitation scenario is a hot leg break where the cold leg high pressure SI may be terminated at or prior to sump recirculation. This scenario is relevant only with the very conservative assumption that all UPI flow in excess of core boil-off bypasses the core region and flows directly out the break (i.e., no mixing in the core and upper plenum).

For Westinghouse-designed and CE-designed plants, boric acid precipitation calculations are used to determine the appropriate time to switch to some or all the ECCS sump recirculation flow to the hot leg or to otherwise show that boric acid precipitation will not occur. For B&W-designed plants, boric acid precipitation calculations are used to justify plant-specific active boric acid dilution methods or limitations on the dilution methods (e.g., plant specific auxiliary pressurizer spray flows, protection of the sump screens, prevention of potential water-hammer scenarios in the decay heat piping, challenges to Net Positive Suction Head (NPSH) limits for Low Pressure Injection (LPI) pumps, hot and cold fluid mixing limits, prevention of boric acid precipitation inside the decay heat cooler, etc.).

The cold leg break post-LOCA boric acid precipitation scenario is represented in Figure 3-1 through Figure 3-3.

3.1 WESTINGHOUSE PWR PLANT DESIGN POST-LOCA BORIC ACID PRECIPITATION MIXING VOLUME ASSUMPTIONS

For Westinghouse-designed PWRs under Westinghouse cognizance, the post-LOCA boric acid precipitation calculations have typically used the following simplifying assumptions in regard to liquid mixing volume:

- Volume does not credit any portion of the lower plenum mixing volume.
- Volume credited in the core is equal to the collapsed liquid volume calculated assuming a hydrostatic balance between the core and the downcomer with the downcomer filled with saturated liquid up to the bottom elevation of the hot leg piping. The loop pressure drop is assumed to be small and is ignored.
- Volume does not include the vessel volume above the bottom of the hot leg elevation.
- Volume does not include any portion of the hot leg volume.
- Volume does not include any portion of the bypass regions (thimble tubes, barrel/baffle regions, etc.).
- Volume does not include any portion of the downcomer.
- Mixing in the core region is complete.

In addition, some plants credit the small increase in core volume that would result from an increased downcomer level that is represented by the "weir height" of the liquid flowing out the break. This credit is commonly referred to as "downcomer overfill" and represents a small volume as compared to the total mixing volume.

Recent analyses for EPU programs have revised the traditional assumptions above in order to address some of the NRC concerns cited in Section 8, Reference 1. Most notably, the calculation of the liquid volume in the core region explicitly considers core voiding and partial mixing in the lower plenum is assumed.

A reactor vessel outline drawing for the Westinghouse PWR design is provided as Figure 3-4.

3.2 CE PWR PLANT DESIGN POST-LOCA BORIC ACID PRECIPITATION MIXING VOLUME ASSUMPTIONS

For CE-designed PWRs under Westinghouse cognizance, the post-LOCA boric acid precipitation calculations have typically used the following simplifying assumptions in regard to liquid mixing volume:

- Volume credits all of the lower plenum mixing volume.
- Volume credited in the core is equal to the collapsed liquid volume calculated assuming a hydrostatic balance between the core and the downcomer with the downcomer filled with saturated liquid up to the bottom elevation of the Reactor Coolant Pump (RCP) discharge legs and with the core collapsed liquid volume further decreased by the differential pressure required to depress the liquid in the downsides of the RCP loop seals to the elevation of the top of the horizontal portion of the loop seal piping.

- Volume inside the Control Element Assembly (CEA) guide tubes up to the elevation credited for the core volume.

- Volume in the core barrel/baffle region up to the elevation credited for the core volume.

- Mixing in the core region is complete.

Recent analyses for the Waterford EPU program have revised the traditional assumptions above in order to address some of the NRC concerns cited in Section 8, Reference 1. Most notably, the calculation of liquid volume in the core region explicitly considers core voiding and partial mixing in the lower plenum is assumed.

A reactor vessel outline drawing for the CE PWR design is provided as Figure 3-5.

3.3 B&W PWR PLANT DESIGN POST-LOCA BORIC ACID PRECIPITATION MIXING VOLUME ASSUMPTIONS

For most B&W-designed PWRs under Areva cognizance, the post-LOCA boric acid precipitation calculations have used the following assumptions in regard to liquid mixing volume:

- The core liquid mixing volume was assumed to be a constant depending on break size, conservatively determined using applicable LOCA thermal-hydraulic codes modeled for the B&W-designed plants. For at least one plant, the core liquid mixing volume varies as a function of decay heat levels and system pressure.

- Mixing volume credits the liquid in the core, core bypass, core baffle region, core upper plenum, and outlet annulus.

- The steam void fraction in these regions reduces the available mixing volume.

- Liquid in the core lower plenum and the horizontal runs of the hot legs was not credited.

- The effects of boiling and core inlet subcooling were credited.

- Mixing in the core region is complete.

The analyses for one plant differed from the above assumptions in that a simple constant core liquid mixing volume was used. The mixing volume included the core, core bypass, core baffle region, and core lower plenum. Liquid in the reactor vessel (RV) above the top of the active fuel region was not credited. No core voiding was considered although the effects of boiling were credited for providing the internal circulation necessary to give a homogeneous boric acid concentration in the mixing volume.

A reactor vessel outline drawing for the B&W PWR design is provided as Figure 3-6.

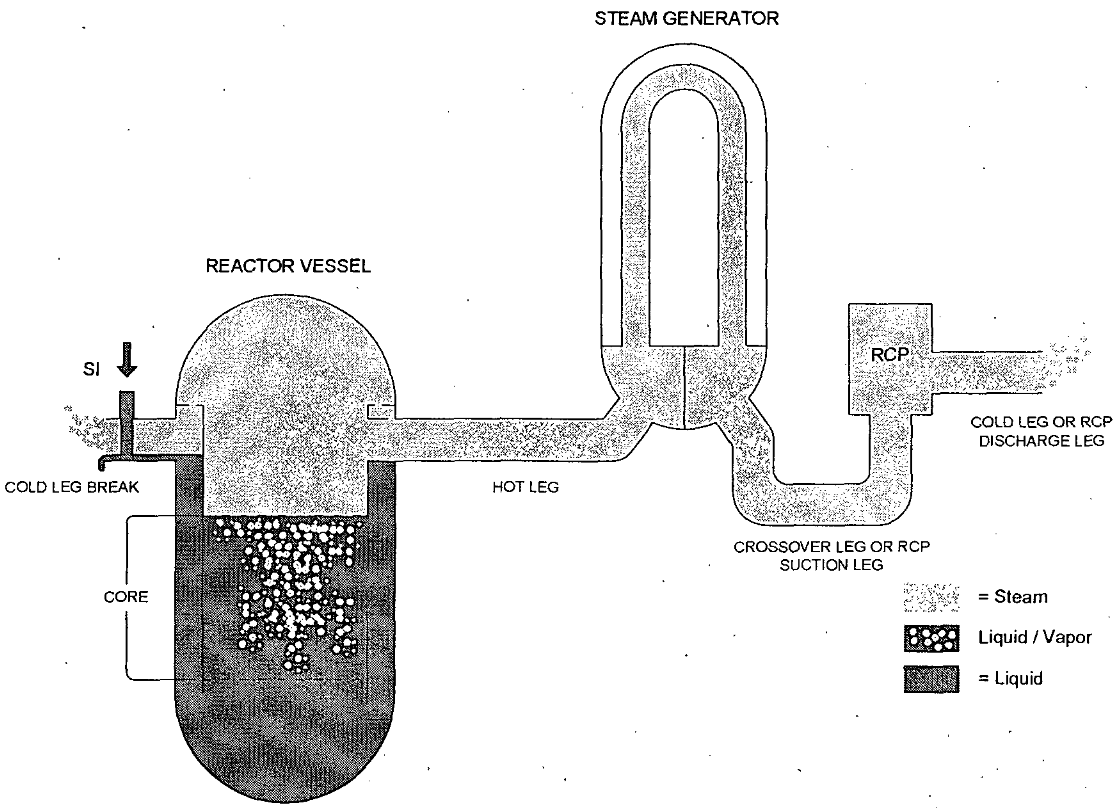

Figure 3-1 Cold Leg Pump Discharge Break, Westinghouse PWRs

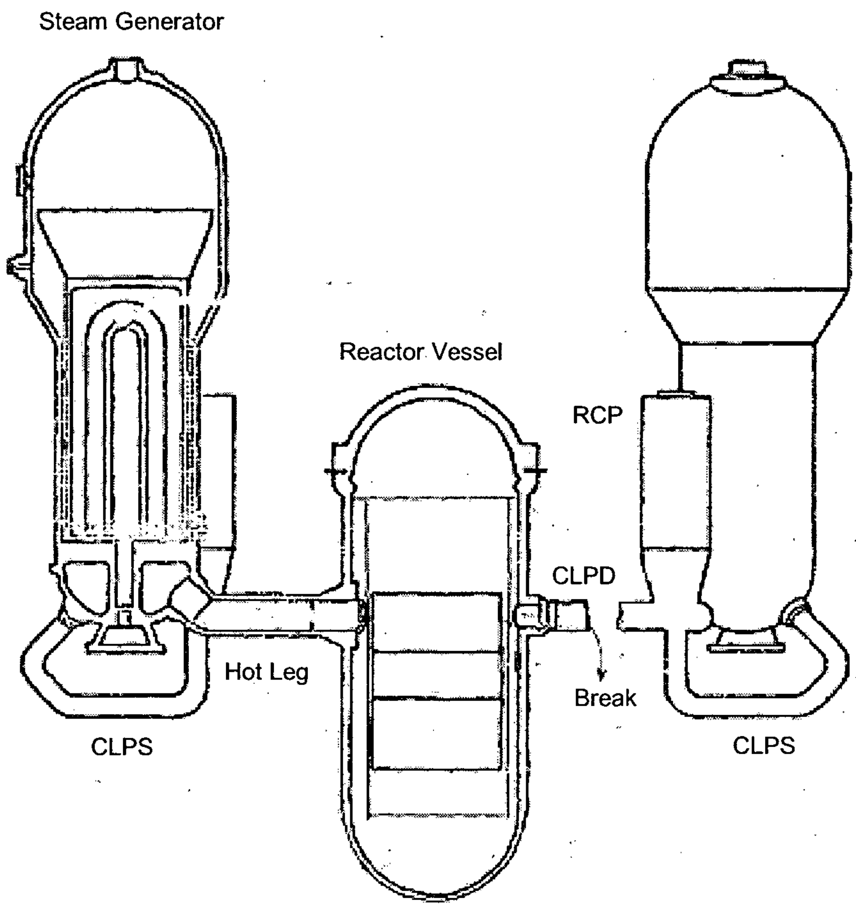

Figure 3-2 Cold Leg Pump Discharge Break, CE PWRs

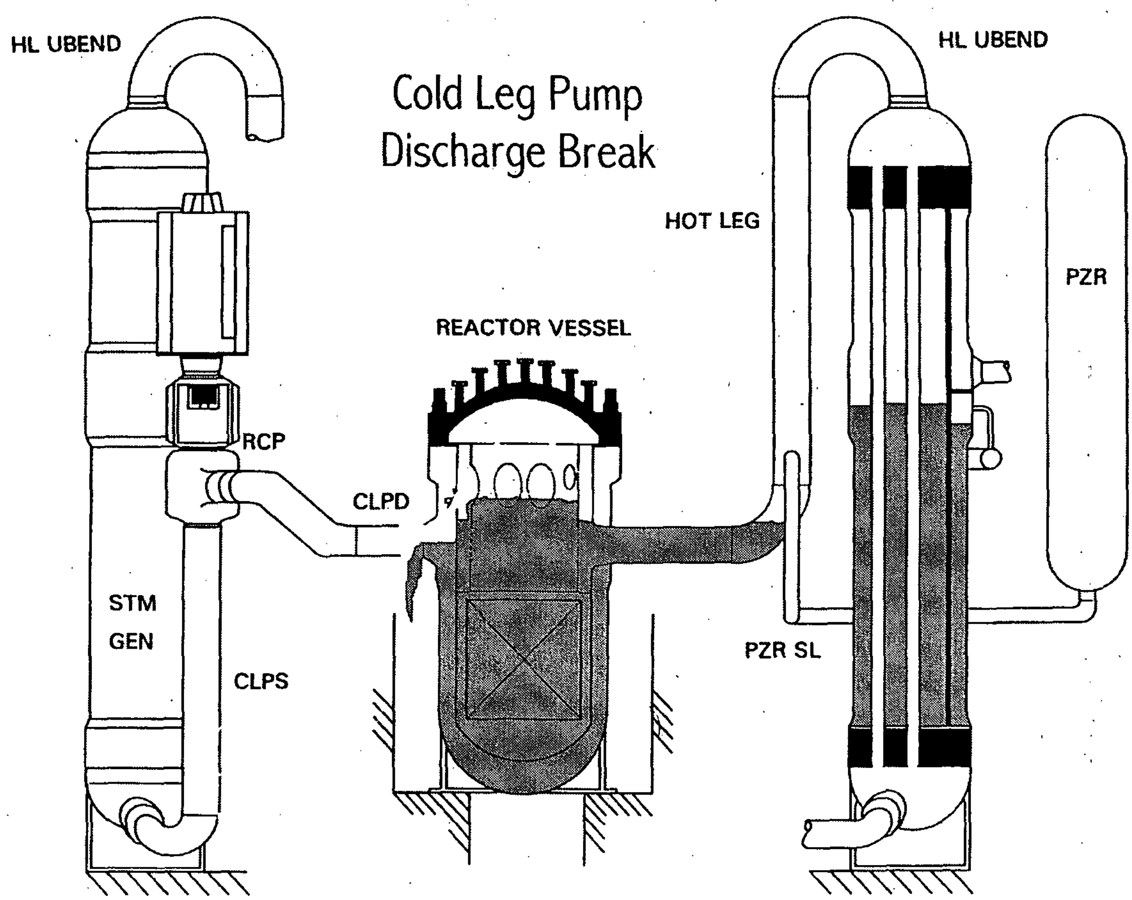

Figure 3-3 Cold Leg Pump Discharge Break, B&W PWRs

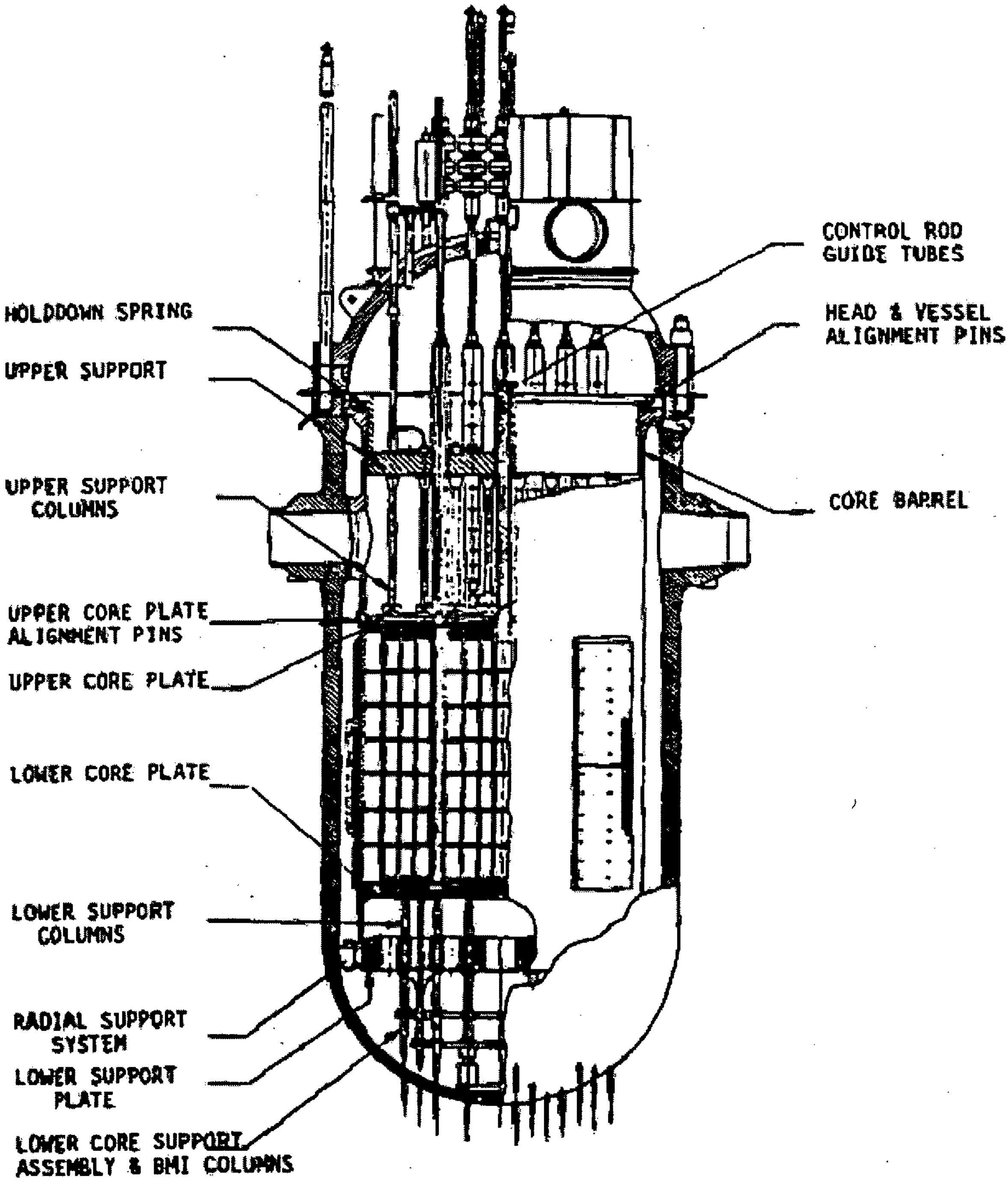

Figure 3-4 Typical Westinghouse Reactor Vessel and Internals Arrangement

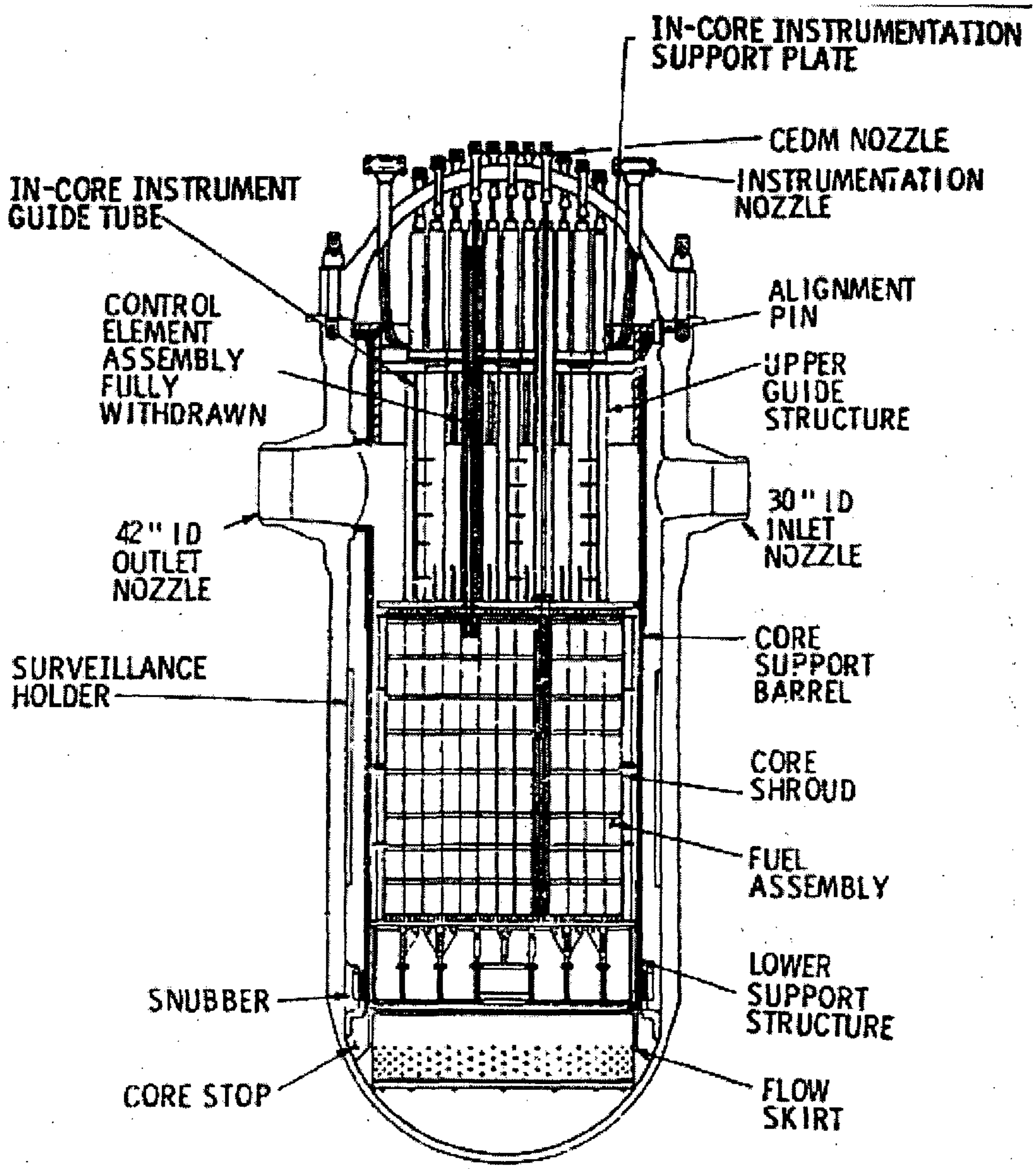

Figure 3-5 Typical CE Reactor Vessel and Internals Arrangement

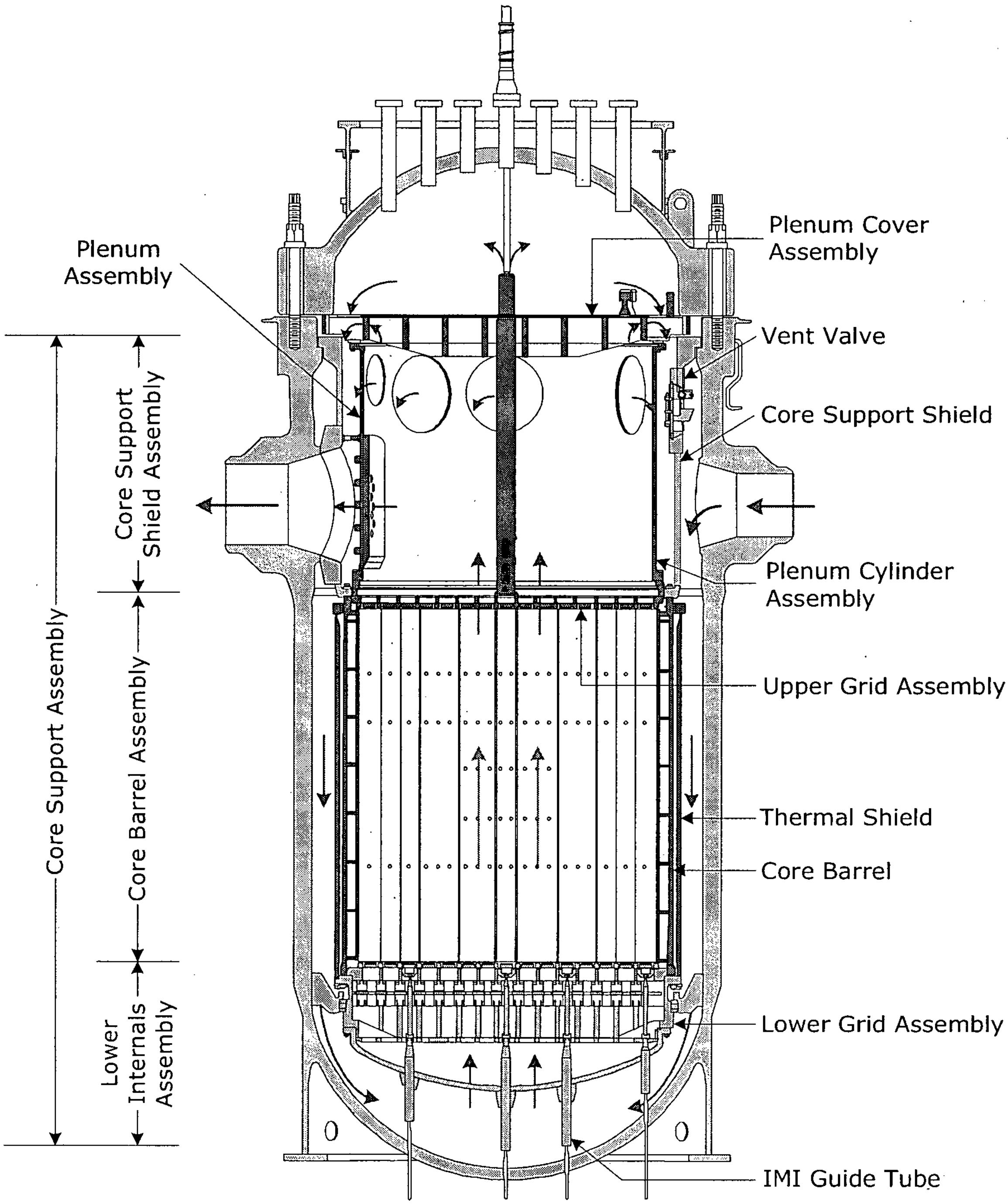

Figure 3-6 Typical B&W Reactor Vessel and Internals Arrangement

4 PIRT PROCESS

The PIRT was developed following the approach outlined in Section, Reference 8. First, a list of plausible phenomena was prepared. Next, phenomena were ranked for importance through the various periods identified for the transient and the state of knowledge was assessed based upon the diverse experience of the PIRT review team. For phenomena that were ranked low and/or N/A for all transient periods, the state of knowledge was not assessed.

Relative rankings of the phenomena in the PIRT were assigned using the following criteria:

H = The phenomenon is considered to have high importance. Modeling of the phenomenon during the particular period is considered to be crucial to obtain the correct or conservative prediction of the transient.

M = The phenomenon is considered to have medium importance. The phenomenon must be modeled with sufficient detail to obtain accuracy in the simulation; however, the phenomenon is expected to have less impact on the overall results than those ranked high.

L = The phenomenon is not considered to be very important during the transient. The phenomenon needs to be modeled in the code (or accounted for in the methodology), but inaccuracies in modeling these phenomenon are not considered likely to have a significant impact on the overall transient results.

N/A = The phenomenon is considered insignificant, or does not occur at all. This phenomenon need not be modeled or be taken into consideration, as it has an insignificant impact on results.

The state of knowledge (SOK) rankings in the PIRT were assigned using the following criteria:

H = The state of knowledge of the phenomenon is considered to be high. Relevant test data exists and mature calculation methods exist. There is sufficient understanding of these phenomena such that they could be treated in a conservative or bounding manner in a model and no new testing or model development is needed to predict these phenomena.

M = The state of knowledge of the phenomenon is considered to be medium. Test data and/or calculation methods that exist may not be directly applicable to the scenario or geometry under consideration. There is sufficient understanding of these phenomena such that they may be treated in a conservative or bounding manner in a model although additional tests or model development will likely be necessary to properly account for these phenomena if the phenomena are high ranked.

L = The state of knowledge of the phenomenon is considered to be low. Little or no relevant test data exists and calculation methods that may exist have not been applied to the scenario or geometry under consideration. There is insufficient understanding of these phenomena such that they cannot be treated in a conservative or bounding manner in a model so tests and/or model development will be necessary to properly account for these phenomena if the phenomena are high ranked.

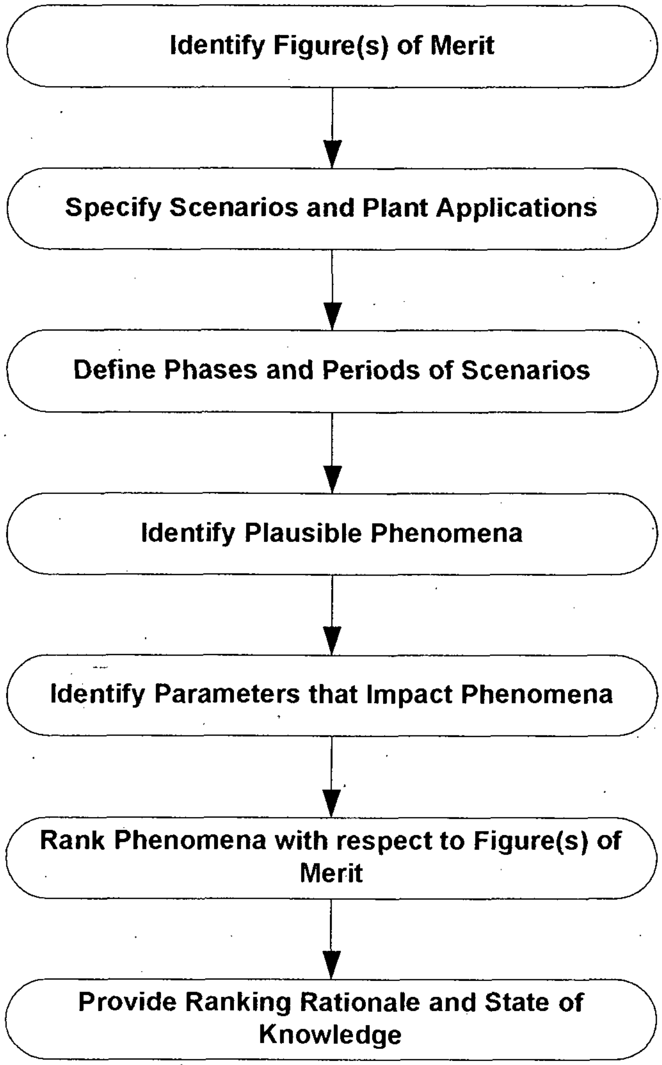

Figure 4-1 PIRT Process

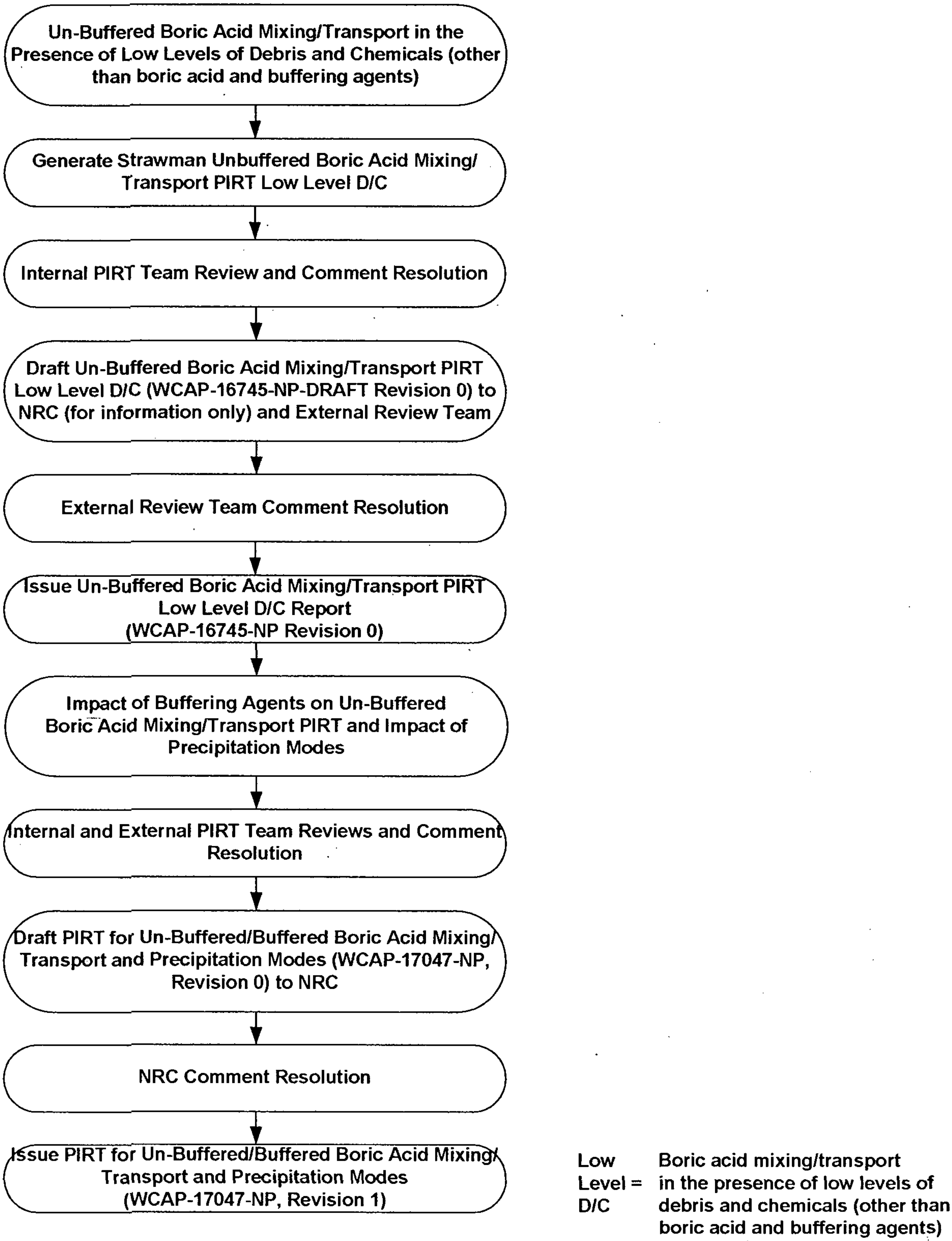

Figure 4-2 PIRT Review Process

5 PIRT REVIEW TEAM

5.1 EXTERNAL EXPERTS

The external experts who comprise the PIRT review team represent the chemical, mechanical, and nuclear engineering disciplines:

- Dr. A. Borhan, Professor of Chemical Engineering, The Pennsylvania State University
- Dr. J. M. Cimbala, Professor of Mechanical Engineering, The Pennsylvania State University
- Dr. L. E. Hochreiter, Professor of Mechanical and Nuclear Engineering, The Pennsylvania State University

Dr. Ali Borhan

Dr. Ali Borhan, has an M.S. and Ph.D. in Chemical Engineering, from Stanford University and B.S. in Chemical Engineering and B.S. in Mathematics from Massachusetts Institute of Technology. Dr. Borhan is a Professor of Chemical Engineering, Penn State University and has earned the Premier Teaching Award, Penn State Engineering Society in 2007 and Outstanding Teaching Award, Penn State Engineering Society, 1994-1995. His research interests include fluid dynamics and hydrodynamic stability of multiphase systems, interfacial transport phenomena, dynamics of complex fluids, wetting and capillary phenomena, applied mathematics and computational methods. Dr. Borhan has chaired numerous technical sessions on fundamental research in fluid mechanics, viscous flows, interfacial flows, interfacial transport, and drop and bubble dynamics at national and international conferences such as the AIChE annual meeting, APS/DFD annual meeting, and ACS symposiums. Dr. Borhan has reviewed over 100 articles for Physics of Fluids, Journal of Fluid Mechanics, Journal of Non-Newtonian Fluid Mechanics, Journal of Computational Physics, Journal of Rheology, Journal of Colloid and Interface Science, International Journal of Multiphase Flow, Computers and Fluids, Experiments in Fluids, Physical Review E, Journal of Biomechanical Engineering, International Journal of Heat & Mass Transfer, Physical Review Letters, Chemical Engineering Science, Chemical Engineering Communication, Industrial & Engineering Chemistry Research, Journal of Heat Transfer, Chemical Engineering Education, Langmuir, Transport in Porous Media, AIChE Journal. Dr. Borhan has published over 50 journal papers, has reviewed textbooks for McGraw-Hill, Wiley, Oxford University Press, CRC Press and over 100 research proposals for National Science Foundation, National Institutes of Health, National Aeronautics and Space Administration, and Petroleum Research Fund of ACS. Dr. Borhan has served on various review/advisory panels for funding agencies, including NASA Microgravity Science and Applications Division (Interfacial Phenomena and Stability Program, Fluid Physics, Fundamental Physics and Combustion Science Program, Microgravity Glovebox), National Institutes of Health, and National Science Foundation.

Dr. John M. Cimbala

John M. Cimbala is Professor of Mechanical Engineering at The Pennsylvania State University (Penn State). He received his B.S. degree in Aerospace Engineering in 1979 from Penn State, his M.S. degree in Aeronautics in 1980 from The California Institute of Technology (Caltech), and his Ph.D. degree in

Aeronautics in 1984 from Caltech under the direction of Professor Anatol Roshko. In July of 1984, Dr. Cimbala returned to Penn State as Assistant Professor of Mechanical Engineering. In July of 1990, he was promoted to Associate Professor of Mechanical Engineering, and was granted tenure. In July of 1997, he was promoted to Professor of Mechanical Engineering. Dr. Cimbala's primary research area is experimental and computational fluid dynamics. Experimental research projects have involved wakes, jets, cylinders with splitter plates, wing-body junction vortices, turbulence, cavitation, indoor air pollution control, elbow wear in particle-laden flow, aerodynamic forces on vehicles, hydroturbines, plasma jet cutting of steel plates, neutron radiography, and heat pipes. During sabbatical leave from 1993 to 1994, he was a Visiting Senior Research Scientist at NASA Langley Research Center, where he studied computational fluid dynamics (CFD). Since that time, Professor Cimbala's research has shifted more towards CFD. Research projects have involved addition and comparison of turbulence models in turbomachinery flow fields, such as cryogenic pumps, hydroturbines, and hydraulic draft tubes, turbulence modeling, direct numerical simulation (DNS) of turbulent wakes, displacement ventilation in rooms, flow in stratified thermal storage tanks, flow in heat pipes, cooling flow in reactor cores, hybrid DNS-RANS turbulence modeling, ventilation in agricultural facilities, and particle resuspension. Dr. Cimbala teaches fluid mechanics, instrumentation, statistics, measurements, thermodynamics, heat transfer, and air pollution courses. He has been instrumental in development of the M.E. Co-op Program, the Undergraduate Fluid Flow Laboratory, and the Instrumentation Laboratory. He has also been a pioneer in development of the Internet for teaching enhancement. Dr. Cimbala is co-author of four widely used textbooks: "Indoor Air Quality Engineering," Marcel-Dekker, 2003; "Fluid Mechanics: Fundamentals and Applications," McGraw-Hill, 2006; "Essentials of Fluid Mechanics: Fundamentals and Applications," McGraw-Hill, 2008; and "Fundamentals of Thermal-Fluid Sciences," Ed. 3, McGraw-Hill, 2008. He is also author or co-author of numerous journal papers and conference proceedings. Professor Cimbala has received several teaching and advising awards, including the 1992 Outstanding Teaching Award from the College of Engineering, the 1996 Premier Teaching Award from the College of Engineering, the 1996-97 Teacher of the Year Award from PSU's branch of Pi Tau Sigma, the 1997 George W. Atherton Award for Excellence in Teaching from Penn State, the 1998 Outstanding Advising Award from the College of Engineering, and the 2006 Greek Week Faculty and Staff Appreciation Award from PSU Fraternities and Sororities. He is a member of the American Society of Aeronautics and Astronautics (AIAA), the American Society of Mechanical Engineers (ASME), the American Society of Engineering Education (ASEE), and the American Physical Society (APS).

Dr. Lawrence E. Hochreiter

Lawrence E. Hochreiter was a Professor of Nuclear and Mechanical Engineering at the Pennsylvania State University. He held a B.S. in Mechanical Engineering from the University of Buffalo, and a M.S. and a Ph.D. in Nuclear Engineering from Purdue University. Dr. Hochreiter spent nearly 26 years working in the Nuclear Energy Systems Divisions at Westinghouse, primarily in the Nuclear Safety area. He initially worked with others in developing the THINC-IV PWR sub-channel analysis code for thermal-hydraulic analysis. In 1972 he was appointed Manager of Safeguards Development (first level manager) and supervised light water reactor safety research, as applied to Pressurized Water Reactors. These experiments included large full-length rod bundle blowdown film boiling, level swell, and reflood heat transfer tests, the NRC/Westinghouse Full Length Emergency Core Heat Transfer (FLECHT) reflooding experiments, the 1/14 and 1/3 scale cold-let steam/water mixing tests, and the Westinghouse Transient DNB tests. He helped develop models and correlations for Westinghouse Appendix K LOCA

Safety Analysis codes and licensed the codes and models with the USNRC, and made numerous presentations to the NRC and to the ACRS.

In 1977 he was appointed to Advisory Engineer and was the Principal Technical Investigator for the NRC/EPRI/Westinghouse Full Length Emergency Core Heat Transfer-Systems Effects and Separate Effects Tests (FLECHT-SEASET) program which examined reflood heat transfer effects in unblocked and blocked rod bundle arrays as well as steam generator effects during reflooding. These experiments also examined the different modes of natural circulation cooling for a PWR following a small break LOCA with different inventories within the reactor system. In addition to the experimental effort, heat transfer models were developed for spacer grids and flow blockages for the COBRA-TF computer code. He also helped develop an analysis and licensing plan for Westinghouse BWR reload fuel assembly designs. He developed and modified the COBRA-TF code to analyze combined radiation and film boiling heat transfer situations for rod bundles with top spray cooling for BWR LOCA situations.

He also served as Westinghouse's safety analysis technical expert for the Three-Mile Island accident. He participated and directed an independent Westinghouse analysis of the accident for the President's Commission on TMI. A detailed presentation was made to the Commission on the analysis performed at Westinghouse. He also served as the Westinghouse representative on the TMI clean-up activities.

He participated in the United Kingdom Reactor Safety Case for the Sizewell PWR application with National Nuclear Corporation and helped develop the safety analysis models that were used in the Sizewell safety analysis and made several presentations to the UK safety authorities as well as the CEGB utility.

In 1987 he was appointed as a Consulting Engineer at Westinghouse. He led a team of Westinghouse engineers to develop a model for the Chernobyl RBMK reactor which was used to explain the accident and the differences in the RBMK design relative to a PWR. These results were presented to the USNRC and the Department of Energy.

He led and participated with engineers to develop a Best Estimate Thermal Hydraulic Methodology, using WCOBRA/TRAC to analyze Westinghouse two-loop reactors with upper plenum injection. He also led and participated with a team of Westinghouse engineers in completing the Best Estimate Loss-of-Coolant Accident Thermal-Hydraulic Safety Analysis Methodology to all pressurized water reactors. This was the first application of the revised 1988 Appendix K rule allowing the Application of Best Estimate Computer models for Loss-of-Coolant Accident Analysis for PWRs. He helped develop the initial PIRT for the Westinghouse plants, performed analysis to address the scaling uncertainty issues, and prepared, with others, the five volume Code Qualification Document for the Westinghouse methodology.

He was responsible for the development and integration of the AP600 (an advanced PWR design) safety testing and analysis efforts which supported the AP600 design certification and licensing. He was directly involved in the model development, refinement, and validation of the Westinghouse safety analysis computer codes for small break LOCA, large break LOCA, long-term cooling, and containment analysis for this passive plant design. He developed several of the initial PIRTs for the AP600 LBLOCA, SBLOCA, transient analysis, and containment analysis. He also performed the scaling analysis for the CMT tests and the Oregon State University APEX low pressure integral systems effects tests. He reviewed and participated in the scaling analysis for the AP600 containment experiments, the SPES full pressure AP600 integral systems experiments, and the ADS experiments. He led a team of engineers in the data analysis of these experiments. He also co-authored the AP600 Scaling and PIRT Closure Report. He also authored and co-authored several of the safety analysis computer code applicability reports which showed that the Westinghouse computer codes were applicable for the AP600 passive safety system design.

Since joining The Pennsylvania State University in January 1997, Dr. Hochreiter continued to work in the safety analysis and development, reactor thermal-hydraulics, reactor safety, and two-phase flow and heat transfer areas. He was the Principal Investigator for the NRC sponsored Rod Bundle Heat Transfer Program which is designed to provide more fundamental experimental data and model development for the NRC advanced computer codes. He was also the Principal Investigator for the Bettis Atomic Power Laboratory Laminar Flow heat Transfer studies, modeling two-phase reactor coolant pump behavior, and validation analysis of the Bettis COBRA/IE-RELAP5 code with the LOFT experiments. He was involved with the Framatome-ANF (Siemens Power Corporation) developing models and analysis methods for new BWR fuel assembly designs for modeling the effects of spacer grids on dryout in BWR bundles. He was also involved with modeling the EPR reactor design with MELCOR severe accident code.

While at Penn State, he consulted with Framatome-ANF (Siemens Power Corporation) on the development of their LBLOCA PIRT and code validation; US Nuclear Regulatory Commission on the development of the High Burnup PIRT, Bettis Atomic Power Laboratory, Idaho Nuclear Laboratory on the development of the LBLOCA PIRT for the Korean KNGR design, Canadian Owners Group on the CANDU BE LOCA and PIRT as well as a High Temperature Fuel Phenomena LOCA PIRT for CANDU fuel and with the Canadian Nuclear Safety Commission in developing guidelines for Best Estimate LOCA reviews.

He won the 2004 Outstanding Teaching Award from the College of Engineering and authored and co-authored over 160 publications in journals, transactions, and proceedings. He also authored and co-authored 90 Westinghouse Reports.

He was a Fellow of the American Society of Mechanical Engineers and a member of the American Nuclear Society.

5.2 INTERNAL EXPERTS

William L. Brown

William L. Brown is a Fellow Engineer at Westinghouse Electric Company's Monroeville, Pennsylvania, office with 27 years of experience in thermal-hydraulic engineering. He obtained his B.A.E. degree from Penn State University and M.S. degree in Mechanical Engineering from the University of Pittsburgh. He spent several years in thermal-hydraulic-acoustic design, analysis, and testing for U.S. Naval nuclear submarines such as the Seawolf, Trident, and Los Angeles class submarines. He successfully led PIRT, scaling, testing, and analysis work to support the development and licensing of new passive commercial nuclear power plants such as the AP600, SPWR, EP1000, IRIS, and AP1000. He received several George Westinghouse Signature Awards for his work in new plant designs including the company's highest level honor in 2001 for AP1000. More recently, Mr. Brown has focused on analysis and testing related to ultrasonic flow meters and turbulent flow phenomena in reactor vessels. Mr. Brown has been an invited lecturer at several universities, an adjunct instructor of engineering mechanics at Penn State University, published several technical papers, and serves as a reviewer of technical papers for Nuclear Technology journal. He is a registered professional engineer licensed in the state of Pennsylvania and a member of ASME.

Dr. William A. Byers

Dr. Byers is a Fellow Engineer at the Westinghouse Electric Science and Technology Department. He received his B.S. degree in Chemistry from Westminster College in 1976 and his Ph.D. in Chemistry from Purdue University in 1982. He has a wide range of teaching and research experience in the fields of nuclear water chemistry and materials characterization. While at Purdue, he developed instrumentation and computer software that related the surface adsorption and electrochemical reactions of nitrodiphenyl-ethers to their herbicidal activity. His early work in industry centered on the monitoring and control of high purity water processes. New methods were developed for the on-line detection of organic acids in nuclear power plant water cycles which solved chemical control problems which had plagued the industry for years. His work on oxygen diffusion in zirconium created acceptance for a new product line in the power industry. Much of Dr. Byers' research has involved the characterization of surfaces and processes occurring at surfaces. His work in the effect of zinc on corrosion processes helped develop zinc addition as PWR primary water additive for inhibition of S/G SCC and dose rate reduction. His most recent work has been directed at understanding of crud deposition and research into the root cause of the PWR Axial Offset Anomaly. Dr. Byers holds 11 U.S. Patents.

Joseph M. Cleary

Joseph M. Cleary is a Principal Engineer at Westinghouse Electric Company's Windsor, Connecticut office and has 30+ years experience in LOCA safety analysis. He obtained his M.S. in Nuclear Engineering from the University of New Mexico. He has expertise in large break LOCA, small break LOCA and post-LOCA long-term cooling safety analysis. His primary expertise is in the application of Appendix K ECCS performance evaluation models to Combustion Engineering PWRs for standard licensing analyses and non-standard applications. He has also been involved in model development, training, and special projects. Mr. Cleary has held various positions within his organization including supervisor of LOCA safety analysis group and certified project manager.

Dr. Milorad B. Dzodzo

Dr. Milorad B. Dzodzo is a Fellow Engineer in the Thermal, Fluid and Nuclear Engineering Group at the Westinghouse Science and Technology Department and is currently working in support of ongoing operations at Westinghouse nuclear divisions and development of advanced nuclear systems. He obtained a B.S. in Mechanical Engineering, M.S. and Ph.D. from University of Belgrade, Serbia. From 1977 to 1978 he was in "Energoproject – Engineering and Consulting Company" and from 1979 to 1992 at the University of Belgrade, Serbia. He was British Council Fellow (1985/1986 school year) and research associate (September 1986 – February 1987) at Imperial College, Computational Fluid Dynamic Unit, London, England. From 1992 to 1996 he was a research associate and visiting assistant professor at The University of Akron, Ohio, USA. He has worked at the Westinghouse Science and Technology Center in Pittsburgh, Pennsylvania, USA since 1996.

Dr. Dzodzo works in the thermal-hydraulic area. His expertise covers the entire range, from analytical approach (i.e., scaling, development of heat transfer correlations, or applying analytical methods for heat transfer and hydraulic problems) to numerical (by developing new and/or improving existing numerical models, or utilizing commercial CFD codes) and experimental (developing new test facilities, modifying existing ones, developing test plans, organizing and performing measurements). His areas of expertise are analysis, numerical modeling and experimental testing in a variety of fields such as: Heat Transfer (natural and forced convection, heat exchangers, stratification and natural circulation inside passive cooled containments of nuclear reactors, heat transfer in the nuclear reactor core), detailed experimental scaling using NRC-approved methodology (applied to the International Reactor Inherently Safe (IRIS) project for Small Break Loss-of-Coolant Accident (SBLOCA) testing), Computational Fluid Dynamics (development of the CFD codes, implementation of higher order numerical schemes in the existing general purpose CFD program, application of NASA developed codes, and application of commercial CFD codes as TascFlow, Star-CD and CFX), Flow Visualization, Tribology, Turbomachinery, Thermodynamics, Heating, Ventilation and Air Condition and Solar Energy conversion.

Dr. Michael Epstein

Michael Epstein is Vice President of Consulting Services at Fauske & Associates, LLC. He received his Ph.D. degree in Mechanical Engineering from the Polytechnic Institute of Brooklyn in 1970. He joined Fauske & Associates in 1980 after nine years of research experience at Argonne National Laboratory, where he was Manager of the Post Accident Heat Removal Section in the Reactor Analysis and Safety Division. He served as a consultant to various industries and on several government (NRC & DOE)/industrial review panels.

Dr. Epstein has published over 100 (archival) journal articles in the areas of fluid mechanics, convective energy and mass transport, phase transformations, aerosol phenomena, and chemical reaction mechanisms. In 1984, he received a National Science Foundation Award to conduct fundamental research on density-driven natural convection. In 1987, he was co-recipient of the William H. Doyle Award for the best paper at the New Orleans Loss Prevention Symposium. He has also participated as an invited speaker and lecturer at several universities and technical symposia and he has served as an advisor to graduate students at several universities. He was a Technical Editor of the ASME Journal of Heat Transfer (1979-1985) and was Chairman of the AIChE's Committee on Safety of Chemical Processes and Hazardous Materials (1988-1991).

Dr. Cesare Frepoli

Cesare Frepoli is a Fellow Engineer at Westinghouse Electric Company's Monroeville, Pennsylvania, office. He has 15 years of experience in the nuclear industry and 27 years experience in the area of thermal-hydraulic engineering. He received a Ph.D. in Nuclear Engineering from Penn State University and an M.E. in Nuclear Engineering from the Politecnico di Milano. Dr. Frepoli is a recognized expert in the area of thermal-hydraulic, fluid-dynamics, numerical methods and physical models for computer simulation of nuclear reactors. He has led various development programs and teams within the industry and authored several publications in the area. He is cognizant of the various licensing and regulatory aspects of safety analyses methodologies, operation and maintenance of PWRs, as well as design certification and safety analysis for new generation nuclear power plants (AP600/AP1000, IRIS, APWR, APR1400).

Brett E. Kellerman

Brett E. Kellerman is a Senior Engineer at Westinghouse Electric Company's Monroeville, Pennsylvania, office. He has been on the Westinghouse staff for 11 years. He obtained his B.S. degree in Nuclear Engineering from Penn State University. Prior to joining Westinghouse, he spent several years working in laboratories primarily involved in radiation measurement and metallurgy. At Westinghouse, he has performed the full range of licensing basis LOCA safety analyses including Appendix K and Best Estimate large break LOCA ECCS performance, Appendix K small break LOCA ECCS performance, LOCA blowdown forces, and long-term cooling with a particular emphasis on Westinghouse 2-loop upper plenum injection plant designs. For the last several years he has primarily been involved in long-term cooling methodology development in support of extended power upratings.

John A. Klingenfus

John A. Klingenfus is an Advisory Engineer at AREVA NP's Lynchburg, Virginia, office. He obtained his B.S. and M.E. Degrees in Engineering Physics with specialties in the thermal and nuclear sciences from the University of Louisville and began work in 1980 in the Babcock and Wilcox nuclear division in Lynchburg, VA. He has been on the AREVA NP staff (formally B&W as well as various other names) for 26 years in various engineering, teaching, and supervisory roles with the primary focus on LOCA analysis code and methods development. He has been responsible for system thermal-hydraulic code benchmarks and performed numerous code development activities for various codes including CRAFT2 and RELAP5/MOD2-B&W system thermal-hydraulic codes. He has led or participated in numerous SBLOCA, LBLOCA, and non-LOCA model and method development tasks for applications on B&W, Westinghouse, CE, and the new US EPR plants. He led the development effort and authored the RELAP5/MOD2-B&W-based LOCA deterministic evaluation model for B&W-designed plants. He also provides regular consultation to the Emergency Operating and Inadequate Core Cooling procedure writers and has developed and supported methods for LOCA mass and energy release and Appendix R analysis efforts. In addition, he has developed methods for demonstrating compliance to the coolable core geometry and long-term core cooling criteria of 10 CFR 50.46. This work included development of the current generic post-LOCA boric acid precipitation methods for small and large LOCA events for the B&W-designed plants.

Mitchell E. Nissley

Mitchell E. Nissley is a Fellow Engineer at Westinghouse Electric Company's Monroeville, Pennsylvania, office. He obtained his B.S. and M.E. Degrees in Nuclear Engineering from Rensselaer Polytechnic Institute. He has worked for Westinghouse Electric Company for 26 years, and has led or consulted with the teams responsible for the development, licensing and application of the various realistic large break LOCA analysis codes and methodologies employed by Westinghouse. His contributions to the nuclear industry include the development and licensing of critical heat flux correlations for advanced PWR and VVER (Vodo-Vodni Energiini Reqktor, also known as Water-Water Energy Reactor) fuel designs, and the development and licensing of realistic large break LOCA evaluation models for Westinghouse PWR designs (cold leg injection, upper plenum injection, AP600/AP1000, and Combustion Engineering designs). He was an Electric Power Research Institute (EPRI)-nominated member of the NRC's High Burn-up Fuel PIRT Panel for the PWR Loss-of-Coolant Accident, and actively participates on the EPRI

Fuel Reliability Program's interactions with the NRC regarding high burn-up LOCA testing results. He has several journal and conference publications.

Dr. Katsuhiro Ohkawa

Katsuhiro Ohkawa is a Fellow Engineer at Westinghouse Electric Company's Monroeville, Pennsylvania, office. He has 24 years of experience in the nuclear industry. He received a B.S. degree in Physics from Sophia University in Tokyo, Japan and M.S. and Ph.D. degrees in Nuclear Science and Engineering from Rensselaer Polytechnic Institute. His experience at Westinghouse includes the development of Advanced Liquid Metal Nuclear Plants, BWR and PWR safety methods and the real time thermal-hydraulic systems code. Since 1990, he has been involved in the development of Best Estimate LOCA Analysis Methods. Currently he is leading the development efforts for the Best Estimate Full Spectrum LOCA Methodology.

6 PIRT PRECIPITATION PROCESSES, SCENARIO IDENTIFICATION, AND ESTABLISHMENT OF PIRT SCENARIO PHASES AND PERIODS

6.1 PRECIPITATION PROCESSES IN A REACTOR VESSEL

Precipitation can be defined as the formation of a solid phase from a chemical solution (liquid phase); or simply as phase separation. Precipitation generally involves the following phenomena or processes:

1. **Formation (establishment of solute-solvent bonding) of chemical solution.** As formation of un-buffered boric acid solution occurs prior to a LOCA event and formation of buffered boric acid solution typically occurs outside of the reactor vessel (such as in the containment sump), molecular-level phenomena related to formation of solution and potential sump debris or sump chemistry effects (i.e., GSI-191 issues) are not addressed in the Reactor Vessel Precipitation Modes or Mixing/Transport PIRTs.

2. **Distribution and accumulation of solute (specifically, spatial distribution and accumulation of solute) within the reactor vessel.** Distribution and accumulation of un-buffered and buffered boric acid solution within the reactor vessel is highly dependent upon global and local/regional phenomena that control mixing/transport of solute within the reactor vessel and are addressed in the Mixing/Transport PIRT tables. As solution temperature distribution is also important to precipitation (solubility depends upon solution temperature) and as much of the same solute mixing/transport phenomena are involved in thermal mixing, mixing/transport phenomena that impact temperature distribution within the reactor vessel are included in the Mixing/Transport PIRT.

3. **Super-saturation (due to boiling, evaporating, or cooling of chemical solution) and formation (nucleation and sustained net growth) of solid phase within the chemical solution or onto "foreign" surfaces within the reactor vessel in contact with the chemical solution.** Super-saturation is a meta-stable state where the concentration of solute exceeds the solubility limit (equilibrium concentration at a given solution temperature). As super saturation and solid phase formation phenomena may occur under different modes within the reactor vessel, these are addressed in the Precipitation Modes PIRT tables.

As it is expected that active dilution measures in a plant will be taken before nucleation and sustained growth is achieved in the reactor vessel, phenomena related to further growth of precipitate such as agglomeration or precipitate aging/breakage are not addressed in this report.

6.2 SCENARIO IDENTIFICATION

The scenarios of high importance with respect to precipitation phenomena in a reactor vessel during post-LOCA conditions are considered to be the following:

- Large, cold leg break post-LOCA scenario

- Some small break post-LOCA scenarios where the RCS experiences sudden depressurization after cessation of two-phase natural circulation through the steam generator/loop piping.

These scenarios are considered to be of high importance as they eventually lead to a "boiling pot" mode where loop circulation and/or liquid entrainment are severally restricted to help limit accumulation of un-buffered or buffered boric acid within the reactor vessel. The large, hot leg break post-LOCA and small break post-LOCA scenarios prior to cessation of two-phase natural circulation generally support high loop circulation through the reactor vessel and liquid entrainment from the reactor vessel to help mitigate the accumulation of un-buffered or buffered boric acid.

The large, cold leg break post-LOCA scenario has some increased importance relative to the small break scenario due to the lower pressure associated with the large, cold leg break as it results in lower solubility limit and lower distribution (or partition) coefficient associated with the presence of un-buffered or buffered boric acid in steam.

Based upon the above consideration, the emphasis of the PIRT phenomena rankings and rationale is on the large, cold leg break post-LOCA scenario.

6.3 PIRT SCENARIO PHASES AND PERIODS

In the PIRT development process, it is useful to divide the scenario into several phases and sub-phases or periods to better identify and rank the phenomena. Many phenomena will be important during one phase or period but may become insignificant or even non-existent during others. In order to successfully predict the entire evolution of the scenario, it is necessary to accurately predict the phenomena during their phase or period of importance. Many of the PIRTs developed to date have looked at scenarios that are fairly well understood, (i.e., the short term small and large break LOCAs), and for which abundant amounts of experimental data exists. Long term cooling has not received the same level of attention and experimental study as the short term transients for peak clad temperature, embrittlement, and hydrogen generation. Given that relatively little is understood about the scenario, it is imperative to rank not just the importance of the phenomenon itself but also the state of knowledge (SOK). This two-part ranking process will better serve to identify the key areas of focus for scaling, testing, and analytical methodology/analytical tool selection.

For the un-buffered/buffered boric acid precipitation modes and mixing/transport PIRTS, the scenario will be divided into two phases:

- Accumulation and Passive Dilution Phase
- Active Dilution Phase (not addressed in current PIRT)

In reviewing the tests, the expert panel recommended the accumulation and passive dilution phase be subdivided into three sub-phases or periods. The three periods are the turbulent and unsteady reactor vessel flow dominated period, transition period, and convection transport dominated period (Figure 6-2). These periods are described in the following sections. The selection of the periods was based upon mixing/transport phenomena (vs. precipitation modes phenomena) as the emphasis prior to precipitation is on phenomena related to the distribution and accumulation of solute.

Finally, it is necessary to define when the post-LOCA, long term cooling PIRT scenario begins for the full spectrum of break sizes as it relates to un-buffered or buffered boric acid accumulation in the reactor vessel. For a Large Break LOCA (LBLOCA), the PIRT scenario begins when the core begins to reflood after the accumulators have refilled the lower plenum following the initial blowdown of the RCS. For a Small Break LOCA (SBLOCA), the PIRT scenario begins once two-phase natural circulation (with continuous liquid phase flow regime in loop piping) breaks down (e.g., annular (countercurrent) or dispersed droplet flow regime in intact loop steam generators) thereby degrading the mechanism for transporting un-buffered or buffered boric acid through the RCS and eventually out the break.

6.4 UN-BUFFERED AND BUFFERED BORIC ACID ACCUMULATION AND PASSIVE DILUTION PHASE

6.4.1 Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period

The decay heat is at its highest during this period. To satisfy decay heat removal, flow from the downcomer, through the lower plenum, core, upper plenum, and then out of the reactor vessel will initially be significant but will decrease as the core decay heat diminishes. This high flow will generate turbulence as the coolant passes through the complex geometries of the reactor vessel internals. Therefore, turbulent dispersion will be the one of the primary mixing mechanism. This turbulent mixing is expected to create local mixing within sub-regions of the reactor vessel, but not global mixing throughout the reactor vessel.

Mixing/transport is also expected from unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects. System interaction effects can produce flow instabilities related to thermal-hydraulic coupling between the reactor vessel, steam generator, and loop piping. Flow oscillations were observed to occur in the FLECHT tests (Section 8, Reference 6, Run 2919) for some time after the rod bundle was quenched.

The available experiments (Section 8, Reference 4 and 5) show that the downcomer and lower plenum region concentration remain relatively close to the source (Refueling Water Storage Tank (RWST) or containment sump) concentration; whereas, the core and upper plenum regions are initially relatively close to the source concentration but continuously increase as the coolant boils away leaving behind the solute. The expected concentration distribution is depicted in Figure 8-1 along with a summary of high-ranked phenomena.

6.4.2 Transition Period

During this period, the coolant flow required to provide make-up for core decay heat boil-off diminishes. As such, the turbulent dispersion mixing mechanism correspondingly diminishes as the flow transitions from turbulent toward laminar. The flow may intermittently cycle between turbulent and laminar with decreasing frequency as the flow becomes more nearly laminar. As the turbulent dispersion of boric acid diminishes, both axial and radial concentration gradients will form thereby effectively “un-mixing” some regions (particularly in the core region) that were previously reasonably well mixed. Concentration gradients between the regions will be such that molecular diffusion will provide some small amount of boric acid transport between regions. The expected concentration distribution is depicted in Figure 8-2 along with a summary of high-ranked phenomena.

6.4.3 Convection Transport Dominated Period

As the decay heat further diminishes, flow to satisfy core cooling may become less turbulent and, with continued boil-off, this would produce larger concentration gradients in the reactor vessel. The concentration gradient would primarily increase through the reactor vessel while the temperature gradient would decrease due to lower decay heat. Increasing the concentration gradient relative to the temperature gradient can lead to density-driven instability and hence convection. If the concentration gradient is large enough so that the net density gradient in the rector vessel is unstable, then convection due to fluid density instability (i.e., denser fluid over top of less dense fluid) is expected to occur analogous to Rayleigh-Bénard convection in single component (i.e., no solute) convection.

The expected concentration distribution is depicted in Figure 8-3 along with a summary of high-ranked phenomena. This period ends when recirculation coolant flows are realigned prior to reaching the solution solubility limit in a region of the reactor vessel.

6.5 ACTIVE DILUTION PHASE

At some point following a LOCA, the Emergency Operating Procedures (EOPs) typically instruct operators to take action to initiate a means of actively diluting the concentrated solution that would be present in the reactor vessel after a cold leg break. The action may involve switching some or all of the pumped safety injection from cold leg injection to hot leg injection (either directly or through pressurizer spray lines). Hot leg injection flow will force liquid flow through the core and out the break on the cold leg. Alternately, hot leg letdown lines may be opened to discharge RCS inventory to the sump thus allowing positive liquid flow through the core. In either case, forced liquid flow through the core (well in excess of decay heat boil-off), or "flushing flow" has been recognized as a highly effective means of diluting the solution in the reactor vessel. Since active dilution mechanisms are highly plant specific, and since the effectiveness of flushing flow on dilution has not been challenged in the regulatory arena, this phase is not being addressed in the current PIRT.

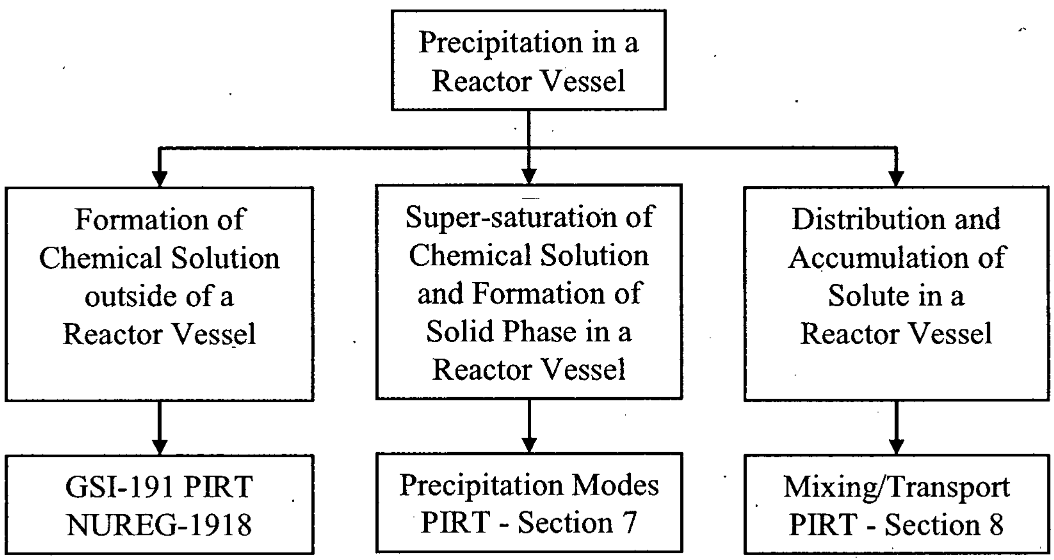

Figure 6-1 Precipitation PIRT Tree

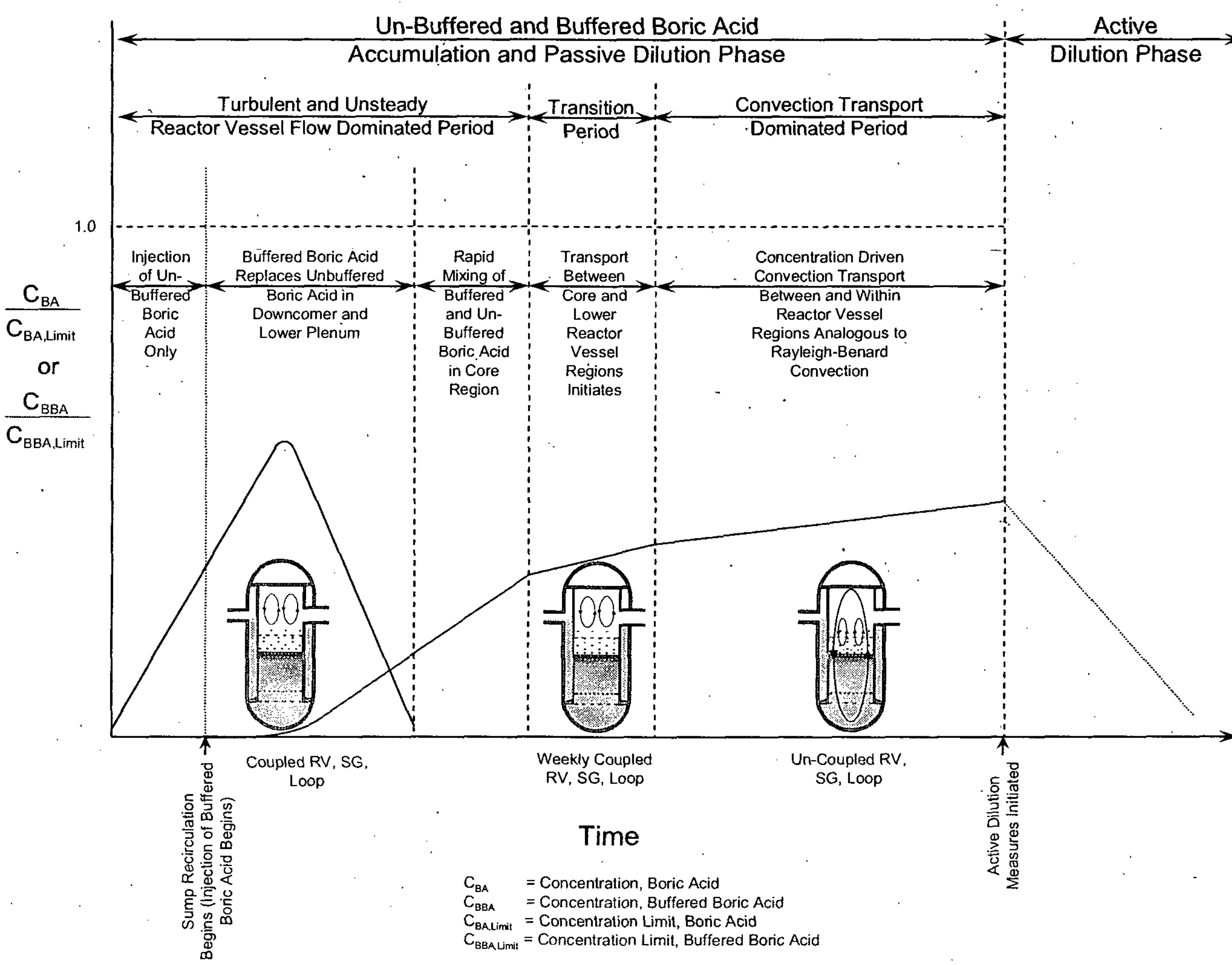

Figure 6-2 Primary Phases and Periods of Post-LOCA Un-Buffered and Buffered Boric Acid Mixing/Transport in Reactor Vessel

7 PIRT FOR PRECIPITATION MODES OF UN-BUFFERED AND BUFFERED BORIC ACID

7.1 PURPOSE AND SCOPE FOR REACTOR VESSEL PRECIPITATION MODES PIRT

The current and historical approach to reactor vessel precipitation has largely been based upon the assumption of a limiting, "bulk" (i.e., total mixing volume) precipitation mode in the reactor vessel. The bulk precipitation mode or limit is predicted from reactor vessel mixing volume and decay heat boil-off calculations to establish bulk concentration as a function of time and applying solubility curves of boric acid solution relating concentration (at saturation condition) to temperature. However, based upon chemical expert review and observations reported in available boric acid precipitation tests such as the Boiling Channel, VEERA/REWET, BACCHUS, and CE tests, a bulk precipitation mode in a reactor vessel is not likely to occur or initiate before other precipitation modes for the following reasons:

- Bulk reactor vessel precipitation has not been seen or reported in any of the available precipitation tests. Even when a rod bundle (VEERA/REWET tests, Reference 11) was subjected to sudden depressurization the simulated reactor vessel regions did not globally precipitate. Precipitation (probably of a readily re-dissolving amorphous form of precipitate) was limited to the high void region of the core/upper plenum region only.

- The reactor vessel volume is not expected to be at a uniform concentration and temperature. While some regions of the reactor vessel such as the core boiling region are expected to be well mixed, concentration and temperature gradients (particularly in the axial direction of the reactor vessel) are expected to exist over most other regions. As temperature is expected to vary throughout much of the reactor vessel volume, the local solubility limit is expected to vary as a function of local/regional temperature in the reactor vessel volume.

- Other precipitation modes have been observed or reported in available precipitation tests. Local precipitation and growth has been observed in the presence of "foreign" surfaces or materials (such as zircaloy heater rods) and local super-saturation due to evaporating (core boiling region) or cooling (lower head region) of the solution. Precipitation of liquid droplets/films on boiling/evaporating surfaces has been observed to occur before the "bulk" concentration of the mixing volume reaches the solubility limit.

Consequently, a Precipitation Modes PIRT for un-buffered/buffered boric acid is needed to address the plausible precipitation modes in various regions of the reactor vessel in post-LOCA conditions as local/regional level phenomena may be important. The Precipitation Modes PIRT addresses the possibility of multiple precipitation modes or limits in various regions of the reactor vessel which depend upon different factors including super-saturation due to boiling/evaporation or cooling, liquid entrainment/de-entrainment, and nucleation and growth on "foreign" surfaces and materials.

7.2 BACKGROUND FOR REACTOR VESSEL PRECIPITATION MODES PIRT

7.2.1 Precipitation as Related to Super-Saturation, Nucleation, and Sustained Net Growth of Solid Phase

7.2.1.1 Solid Growth Forms Expected in Reactor Vessel

Precipitation in a reactor vessel following a design basis accident such as a LOCA is expected to be of two primary forms:

- Crystalline (highly-ordered, compact structure). The crystalline form was mostly observed in the lower region (below the heated section of the simulated fuel rod) of the Boiling Channel Test (Reference 19) and CE Test. However, some small amount was seen in the steam separator region of the Boiling Channel Test as well. Crystalline precipitate is a more stable form of precipitate which dissolves only from the outside and hence does not tend to dissolve quickly. The growth rate of crystalline precipitate is driven by the mass transfer coefficient (of solute molecules transported from the bulk solution to the crystal surface) and by the level of super-saturation. Based upon a mass transfer coefficient that is diffusion limited, the growth rate is expected to be much less than amorphous type precipitates; this behavior was observed in the Boiling Channel Test.

- Amorphous solid (less ordered structure with numerous voids resulting in a significantly higher specific volume compared to the crystalline form). The amorphous solid was mostly observed in the upper heated region of the Boiling Channel Test such as near or above the two-phase mixture level. Amorphous solid precipitate is a less stable form which can dissolve from within (due to presence of voids) when exposed to a continuous liquid phase. This leads to faster dissolution as evidenced in the Boiling Channel Tests. The growth rate of the amorphous solid is driven by high levels of super-saturation which is dependent upon the local rate of evaporation of the solvent from the solution and the replenishment rate of solute to the surface (which is dependent upon the flow regime).

In summary, in regions of the reactor vessel where lower levels of super-saturation exist it is expected that crystalline forms of precipitate will be produced, whereas, in regions of the reactor vessel where higher levels of super-saturation can exist it is expected that more amorphous forms of precipitate will tend to be produced.

7.2.1.2 Amorphous Solid

The nucleation and growth of an amorphous form of the solid phase on a "foreign" surface is largely dependent upon the level of super-saturation and surface adherence properties. High levels of super-saturation are usually associated with amorphous solid formation. Hence, amorphous solid formation below the two-phase or boiling region of a reactor vessel would most likely be driven by rapid or large sub-cooling of the solution. Amorphous solid formation within or above the two-phase region of a reactor vessel would largely be driven by the local rate of evaporation of the solvent and the replenishment rate of the solution to the "foreign" surface. The replenishment rate would depend upon the two-phase flow regime and rates of entrainment/de-entrainment responsible for transporting liquid solution to the foreign surface. Based upon observations from the Boiling Channel Tests, the growth rate of amorphous precipitate (particularly when the heated rod was un-covered) can be noticeably faster than for crystalline precipitate forms.

7.2.1.3 Crystalline Solid

The growth of a crystalline form of the solid phase on a "foreign" surface is initially governed by diffusion and the level of super-saturation which can generally be expressed as a power law form where the growth rate is a function of the mass transfer coefficient and super-saturation to a power *n* (where *n* is usually between 0 and 2.5) as follows:

$$Growthrate = k(\Delta C)^n$$

where:

k = mass transfer coefficient
ΔC = super-saturation ($C-C_{saturation}$)

The mass transfer coefficient (*k*) depends upon hydrodynamic conditions (as they impact kinetics), temperature, crystal structure, and the presence of impurities. Solute molecules must be transported to the surface (usually by diffusion) and then integrated or organized into a crystal lattice.

Consideration of Gibbs free energy and classical nucleation theory (References 1-5, 12) for a spherical solid nucleus demonstrates that a critical size is needed for sustained net growth of a crystalline solid phase. Although homogeneous nucleation and growth of a spherical nucleus is not expected in a reactor vessel, it is instructive to begin with Gibbs free energy for homogeneous nucleation as it can be used to formulate Gibbs free energy for heterogeneous nucleation and growth.

The Gibbs free energy for homogeneous nucleation and growth of a solid phase from a liquid solution can be expressed as follows for a spherical nucleus of radius, r:

$$\Delta G_{\substack{\text{TOTAL, homogneous} \\ \text{nucleation}}} = \frac{4\pi}{3} r^3 \Delta G_{\text{volume}} + 4\pi r^2 \gamma$$

where:

r = radius of solid growth
γ = solid-liquid interfacial tension
G = Gibbs free energy

The Gibbs free energy expression above represents the total free energy change associated with formation of a nucleus. The first term on the right hand side represents the volume related energy while the second term represents the surface related energy. ΔG_{volume} within the first term represents the thermodynamic driving force for the phase change (formation of the solid phase). If the nucleus can reach a critical value of radius (r^*), then the Gibbs free energy will decrease if the nucleus continues to grow in size as the concentration or super-saturation of the solute in solution decreases. If super-saturation of the solution decreases below that corresponding to critical Gibbs free energy for nucleation, no additional nuclei would form. However, the existing precipitate will continue to grow as long as the concentration of the solution is above the equilibrium concentration.

The critical radius (r^*) size can be found by differentiating the Gibbs free energy expression above with respect to r and setting the result equal to zero. The result for the minimum size of a stable spherical nucleus then becomes:

$$r^* = -2\frac{\gamma}{\Delta G_{\text{volume}}}$$

The associated critical energy barrier that a nucleation process must overcome for sustained net growth can be found to be:

$$\Delta G^* = \frac{16\pi\gamma^3}{3\left(\Delta G_{\text{volume}}\right)^2}$$

The Gibbs free energy change associated with heterogeneous nucleation on a "foreign" surface (which is the expected mode of nucleation in a reactor vessel) can be formulated in relation to the Gibbs free energy change associated with homogeneous nucleation shown above and a surface contact factor ($f(\theta)$) that is a function of the wetting or contact angle between the phases.

$$\Delta G_{\substack{\text{TOTAL, heterogeneous}\\ \text{nucleation}}} = f(\theta)\Delta G_{\substack{\text{TOTAL, homogneneous}\\ \text{nucleation}}}$$

$$f(\theta) = \frac{(2+\cos\theta)(1-\cos\theta)^2}{4}$$

where:

θ = wetting or contact angle between solid and liquid phases

From the above expression, it can be seen that a lower Gibbs free energy barrier is generally associated with heterogeneous nucleation and growth relative to homogeneous nucleation and hence heterogeneous nucleation and growth is often favored over homogeneous. Above the critical Gibbs free energy barrier, both nucleation and growth occur simultaneously, however, the growth rate of the solid phase is usually much lower than the rate of nucleation.

Optical measurements reported in the open literature (References 6-8) for single borax crystals provide some indication of the order of magnitude of crystal precipitate growth rate. For conditions in these tests, crystal growth rate is of the order of 1 μm/min for a relative super-saturation range of 0.28 to 1.0. While extrapolation of such results to a reactor vessel should be done with caution as the hydrodynamic conditions and kinetics in these laboratory tests are not necessarily prototypic of a reactor vessel, they nonetheless provide some idea of the order of magnitude. Based upon observations from the Boiling

Channel Tests (Reference 19), the growth rate of a crystalline form of precipitate is noticeably slower than amorphous forms of precipitation growing on rapidly evaporating surfaces.

7.2.2 Nucleation Processes Most Relevant to Precipitation in Reactor Vessel

The precipitation of buffered or un-buffered boric acid solutions, especially for reactor vessel regions below the two-phase mixture level, is highly dependent upon nucleation. Nucleation requires super-saturation with respect to the solute in solution. The rate of nucleation tends to increases exponentially with super-saturation level. Nucleation can, in general, be categorized into primary nucleation and secondary nucleation.

- Primary nucleation covers nucleation that occurs in a crystal-free solution. In other words a solution that has not been seeded with crystals.

- Secondary or contact nucleation covers nucleation that occurs through contact or collision (usually through agitation or mechanical mixing) between crystals already present in the chemical solution. Secondary or contact nucleation may occur in the boiling channels of a reactor core, but, are usually associated with industrial mixing apparatus and is not expected to be the dominant mode of nucleation in a reactor vessel.

Primary nucleation can be further categorized into homogeneous and heterogeneous nucleation.

- Homogeneous nucleation refers to that which occurs spontaneously and randomly in a pure, bulk, chemical solution. It is induced by a higher level of super-saturation of the solute in the solution as opposed to the presence of foreign particles or surfaces. Super-saturation can be achieved by reducing the amount of solvent via evaporation or boiling or by super-cooling the solution below its solubility limit. Homogeneous nucleation is difficult to achieve except in a very clean, smooth, test tube or beaker.

- Heterogeneous nucleation refers to that which occurs in the presence of foreign particles or surfaces such as rough walls. Heterogeneous nucleation can occur at lower levels of super-saturation compared with homogeneous nucleation. Therefore, heterogeneous nucleation can be more limiting or initiate much earlier than homogeneous nucleation with respect to precipitation. The presence of foreign particles or surfaces can significantly lower surface energy barriers to nucleation which favors heterogeneous nucleation and growth. Hence, the characteristics related to material, size, and surface topology of the foreign particles or surfaces is important for this mode of nucleation. Heterogeneous nucleation occurs far more commonly than homogeneous nucleation.

Consequently, the most likely form of nucleation in a reactor vessel is primary vs. secondary nucleation. The most likely mode of primary nucleation in a reactor vessel is heterogeneous nucleation. Consequently, secondary nucleation and homogeneous nucleation will not be addressed in the Precipitation Modes PIRT tables as they are not very plausible or practical modes of nucleation in a reactor vessel.

7.2.3 Plausible Precipitation Modes in a Reactor Vessel

Plausible precipitation modes seen in the available reactor vessel precipitation tests and identified by PIRT chemical experts are discussed in the table below.

Table 7-1 Plausible Precipitation Modes in a Reactor Vessel
Precipitation (amorphous solid with voids) associated with rapid evaporation (boiling) and super-saturation of entrained liquid solution on heated surfaces above two-phase mixture level. Precipitation associated with entrained liquid solution on heated surfaces above the two-phase mixture level may occur well before the bulk solution reaches super-saturation in the reactor vessel. This precipitation mode has been observed in the Boiling Channel Test. Precipitation above the two-phase mixture level was also reported in the VEERA/REWET and CE tests. When an entrained liquid droplet/film contacts a heated surface, the solvent may be rapidly evaporated. The resulting highly concentrated (super-saturated) droplet adheres to the surface (typically observed as a solute ring pattern in the Boiling Channel Test) in the form of an amorphous solid. The process may be so rapid that there does not appear to be enough time for the solute molecules to organize into a highly ordered crystalline structure. The amorphous solid precipitate form does not show evidence of strong intermolecular bonds as the structure adhering to the heater rod surface is readily re-dissolved when re-contacted with sufficient supply of liquid. Consequently, in regions where there is sufficient liquid supply, it is unlikely that such a form of precipitate could be maintained, especially for plants capable of hot leg/upper plenum safety injection.
Precipitation on boiling surfaces in high void, two-phase region associated with bubble film (micro-layer film at base of bubble) evaporation and super-saturation. Precipitation on boiling surfaces in high void region associated with bubble film evaporation and super-saturation may occur well before bulk solution reaches super-saturation. The micro-layer film at the base of the bubble forming on a boiling surface could rapidly evaporate, super-saturate the film and precipitate on the surface. Similarly, for other two-phase conditions such as slug flow regime within a heated rod bundle only liquid films may exist locally on the heated rod bundle surfaces. The thin films could quickly evaporate and concentrate solute in the films and precipitate. The growth rate would be impacted by the film flow, evaporation rate, and film replenishment rate. For the slug flow regime, the replenishment rate would depend upon the size, velocity, and frequency of slug bubbles. Slow moving or stalled slug bubbles are expected to maximize this mode of precipitation. Unlike the single rod geometry in the Boiling Channel Test configuration, precipitation and growth within a rod bundle could extend from multiple sides toward one another. This would increase the chance for blockage and flow interruption. This type of precipitation growth behavior seems consistent with what was reported in the VEERA/REWET tests. This precipitation mode was not reported in the BACCHUS tests.
Precipitation (crystalline solid) of entrained liquid solution above two-phase mixture level on cooled or condensing surfaces. When entrained liquid is carried to a cooled surface above the two-phase mixture level such as a steam generator tube or channel head, there is the potential for the droplet to become super-saturated and experience heterogeneous nucleation and growth on the surface. The potential for this has been seen in Boiling Channel Tests where small quantities of crystals were observed on the steam separator mesh. Other available tests (BACCHUS, CE, VEERA/REWET) did not include steam generator entrainment simulation.
Precipitation on cooled surfaces, walls, and structures associated with local super-saturation and heterogeneous nucleation. Precipitation can occur on walls and structures when sufficient super-saturation level is reached, especially on cooled surfaces. Heterogeneous nucleation can occur on surfaces where super-saturation exists in the chemical solution and the surface energy barrier is low or reduced due to favorable surface characteristics. This form of precipitation has been observed in the Boiling Channel test and was reported in the CE and VEERA/REWET tests. Due to limited optical access, it is not known if this mode of precipitation occurred in the BACCHUS test.

Table 7-1 (cont.) Plausible Precipitation Modes in a Reactor Vessel
Precipitation (crystalline solid) in bulk solution in unconfined fluid region associated with super-saturation and heterogeneous nucleation (due to the presence of normal impurities). Precipitation in the bulk solution could occur when concentration level leads to a high level of super-saturation within the fluid and it nucleates throughout the bulk region of fluid on normal impurities present in the fluid. This mode of precipitation was not reported in BACCHUS, VEERA/REWET, CE test, or observed in the Boiling Channel test. In the absence of sump debris, the quantity of impurities and bulk level of super-saturation is not expected to be sufficient to support precipitation and growth in the bulk region before the initiation of other modes of precipitation. For certain sump debris or chemistry effects that are beyond the normal level of impurities, the relative importance of this precipitation mode may increase.
Precipitation on walls and structures above two-phase mixture level associated with liquid film/droplet evaporation (non-boiling) and super-saturation. Although precipitation is expected to be more pronounced on boiling surfaces, precipitation may also occur on walls and surfaces where liquid films/droplets evaporate (non-boiling) leading to super-saturation of solute in the liquid solution. This precipitation mode was observed in the Boiling Channel Test. Evaporation of the liquid films/droplets may be driven by several phenomena including direct evaporation (of solvent) to superheated steam (if core un-covery occurs), surface heating from local steam superheat (if core un-covery occurs) or by partial pressure difference between the liquid and vapor phases as a result of the presence of non-condensable gases (i.e., the containment sump is a large source of non-condensable gases that may get dissolved into solution which after injected into the reactor vessel are subsequently released in the core boiling region). This precipitation mode may have occurred in the CE and VEERA/REWET tests, however, it was not reported for the BACCHUS test.
Precipitation on boiling surfaces in low void region (sub-cooled nucleate boiling) associated with bubble film (micro-layer film at base of bubble) evaporation and super-saturation. Precipitation on boiling surfaces in low void region associated with bubble film (micro-layer film at base of bubble) evaporation and super-saturation has been shown to occur on heated rods during sub-cooled nucleate boiling (References 9-10). Experimental work available from the open literature (Reference 9) shows no significant deposition of boric acid onto nucleate boiling rods at high pressure (~1000 psia) with low heat flux (under ~50 kw/m^2); hence no significant amount of additional precipitation is expected for post-LOCA long term cooling conditions unless there was core un-covery or channel blockage that could significantly increase the heat flux through the fuel rod. This precipitation mode was not observed in the Boiling Channel Test and was not reported in BACCHUS, CE, or VEERA/REWET tests.
Precipitation associated with liquid solution confinement within small channels. When the spacing between solid surfaces in a confined channel is on the order of microns, transition from continuum (i.e., bulk) toward non-continuum (i.e., intermolecular or van der Waals forces) effects on precipitation may become important (References 15-17). The chemical solution may act as a more concentrated solution relative to an unconfined, bulk situation and lead to interaction between the chemical solution and solid surface; the interactions occurring on the order of microns. Consequently, it is not expected that this phenomenon within confined spaces will have much impact on precipitation unless the channels become restricted or blocked due to the presence of debris or growing precipitate. This precipitation mode was not reported in the BACCHUS, CE, or VEERA/REWET tests. As the Boiling Channel Test only simulated a single heated rod (vs. a rod bundle), confinement effects did not occur.

7.3 FIGURE OF MERIT: PRECIPITATION MODES

Figure Of Merit: Precipitation Modes
Buffered or Un-Buffered Boric Acid Concentration Local/Regional/Bulk Limit

The figure of merit for the Precipitation Modes PIRT is the buffered or un-buffered boric acid concentration (local, regional, or "bulk") limit which corresponds to an initiating precipitation mode in a reactor vessel region.

7.4 PIRT RANKING TABLES FOR PRECIPITATION MODES IMPACTING REGIONAL PRECIPITATION LIMIT

The following Precipitation Modes PIRT tables summarize the rankings of the most plausible precipitation modes that lead to initiation of sustained net growth of solid phase in the steam generator, hot legs, and various regions of the reactor vessel. As initiation of precipitation in the cold leg/pump region was considered to be very unlikely relative to other regions (due to much lower concentration level), no further evaluation was made of this region. Even though the precipitation and mixing/transport phenomena are the same during Period 1, this period is further subdivided (Period 1a, 1b, and 1c) to account for the introduction of buffered boric acid into the reactor vessel (i.e., Period 1b onward).

Table 7-2a Precipitation Modes Impacting Regional Precipitation Limit – Core Boiling Region

	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						**Transition Period**		**Convection Transport Dominated Period**	
	Period 1a		**Period 1b**		**Period 1c**		**Period 2**		**Period 3**	
	Un-Buffered Boric Acid		**Un-Buffered/ Buffered Boric Acid**		**Buffered Boric Acid**					
Phenomena Description	**Rank**	**SOK**	**Rank**	**SOK**	**Rank**	**SOK**	**Rank**	**SOK**	**Rank**	**SOK**
1. Precipitation (amorphous solid with voids) associated with rapid evaporation (boiling) and super-saturation of entrained liquid solution on heated surfaces above two-phase mixture level. (APPLICABLE TO CORE UNCOVERY ONLY)	H	L	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	H	L	Same as Period 1c		Same as Period 1c	

Table 7-2a (cont.) Precipitation Modes Impacting Regional Precipitation Limit – Core Boiling Region										
	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						**Transition Period**		**Convection Transport Dominated Period**	
	Period 1a		**Period 1b**		**Period 1c**		**Period 2**		**Period 3**	
	Un-Buffered Boric Acid		**Un-Buffered/ Buffered Boric Acid**		**Buffered Boric Acid**					
Phenomena Description	**Rank**	**SOK**	**Rank**	**SOK**	**Rank**	**SOK**	**Rank**	**SOK**	**Rank**	**SOK**
a. Impact of two-phase flow regime on liquid solution entrainment/de-entrainment to/from surface.	H	M	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	H	M	Same as Period 1c		Same as Period 1c	
b. Impact of surface temperature/heat flux on evaporation rate of solvent.	H	M			H	M				
c. Impact of heated surface characteristics such as material and surface topology.	H	L			H	L				
2. Precipitation on boiling surfaces in high void, two-phase region associated with bubble film (micro-layer film at base of bubble) evaporation and super-saturation.	H	L			H	L				
a. Impact of two-phase flow and boiling regime.	H	M			H	M				
b. Impact of surface temperature/heat flux on evaporation rate of solvent.	H	M			H	M				

Table 7-2a (cont.) Precipitation Modes Impacting Regional Precipitation Limit – Core Boiling Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
c. Impact of heated surface characteristics such as material and surface topology.	H	L	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	H	L	Same as Period 1c		Same as Period 1c	
d. Impact of froth behavior.	L				L					
3. Precipitation on walls and structures above two-phase mixture level associated with liquid film evaporation (non-boiling) and local super-saturation. (APPLICABLE TO CORE UNCOVERY ONLY)	H	L			H	L				
a. Impact of two-phase flow regime.	H	M			H	M				
b. Impact of surface characteristics such as material and surface topology.	H	L			H	L				
c. Impact of superheated steam on film/droplet evaporation.	H	L			H	L				

Table 7-2a Precipitation Modes Impacting Regional Precipitation Limit – Core Boiling Region (cont.)

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
4. Precipitation (crystalline solid) in bulk solution of unconfined fluid associated with super-saturation and heterogeneous nucleation (due to presence of impurities).	M	M	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	L		Same as Period 1c		Same as Period 1c	
5. Precipitation on boiling surfaces in low void region (sub-cooled nucleate boiling) associated with bubble film (micro-layer film at base of bubble) evaporation and super-saturation.	L				L					
6. Precipitation associated with liquid solution confinement within small channels.	L				L					

Table 7-2b	Rationale for Precipitation Mode Rankings – Core Boiling Region
1.	For post-LOCA situations where the core may become uncovered, precipitation associated with entrained liquid solution is ranked H as it may occur well before the bulk solution reaches super-saturation in the core region. This precipitation mode has been observed in the Boiling Channel Test, reported in VEERA/REWET tests and may have occurred in the CE test. In the Boiling Channel Test, this precipitation mode was seen for un-buffered and buffered boric acid solutions.
2.	Precipitation on boiling surfaces in a high void region associated with bubble film (micro-layer film at base of bubble) evaporation and super-saturation is ranked H as this mode does not require a high bulk concentration to reach local super-saturation due to the boiling and evaporation in the core. This precipitation mode was not explicitly observed in the Boiling Channel tests as it was not a rod bundle type test, however, this mode may have occurred in VEERA/REWET and CE rod bundle type tests. Due to the rapid evaporation rates, both un-buffered and buffered boric acid solutions are ranked H.
3.	This mode of precipitation is ranked H as local concentration may reach super-saturation due to evaporation for buffered or un-buffered boric acid.
4.	This mode of precipitation is ranked M as is not likely to occur before other modes of precipitation nor result in significant precipitation and growth such as associated with heterogeneous nucleation on walls and surfaces. The mode was not seen in the Boiling Channel Test and was not reported in BACCHUS, VEERA/REWET, and CE tests. For buffered boric acid, this mode is ranked L due to the significantly higher solubility.
5.	Precipitation on sub-cooled nucleate boiling surfaces is ranked L as it only reported to occur at higher heat fluxes than associated with post-LOCA conditions. Boiling Channel Test observations reported no visible precipitation on simulated zircaloy fuel rod with sub-cooled inlet conditions and no degradation in heat transfer.
6.	Precipitation due to confinement effects are not expected to occur as the spacing between fuel rods is not small enough (in the absence of debris or precipitation).

Table 7-3a Precipitation Modes Impacting Regional Precipitation Limit – Core Non-Boiling Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Precipitation on walls and structures associated with local super-saturation and heterogeneous nucleation.	M	L	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	L		Same as Period 1c		Same as Period 1c	
2. Precipitation (crystalline solid) in bulk solution of unconfined fluid associated with super-saturation and heterogeneous nucleation (due to presence of impurities).	M	M			L					
3. Precipitation associated with liquid solution confinement within small channels.	L				L					

Table 7-3b Rationale for Precipitation Mode Rankings – Core Non-Boiling Region

1.	This mode of precipitation is ranked M for un-buffered boric acid as the local super-saturation level is not expected to be high enough to initiate precipitation before other modes such as associated with heated or boiling surfaces. Buffered ranking is L due to higher solubility.
2.	This mode of precipitation is ranked M for un-buffered boric acid as is not likely to occur before other modes of precipitation nor result in significant precipitation and growth such as associated with heterogeneous nucleation on walls and surfaces. The mode was not seen in the Boiling Channel Test and was not reported in BACCHUS, VEERA/REWET, and CE tests. Buffered ranking is L due to higher solubility.
3.	Precipitation due to confinement effects are not expected to occur as the spacing between fuel rods is not small enough (in the absence of debris or precipitation).

Table 7-4a Precipitation Modes Impacting Regional Precipitation Limit – Barrel/Baffle Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Precipitation on walls and structures above two-phase mixture level associated with liquid film/droplet evaporation (non-boiling) and super-saturation. (APPLICABLE TO CORE UNCOVERY ONLY.)	H	L	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	H	L	Same as Period 1c		Same as Period 1c	
a. Impact of heated surface characteristics such as material and surface topology.	H	L			H	L				
b. Impact of superheated steam on film/droplet evaporation.	H	L			H	L				
2. Precipitation on walls and structures associated with local super-saturation and heterogeneous nucleation.	M	L			L					
3. Precipitation associated with liquid solution confinement within small channels.	L				L					

Table 7-4b	Rationale for Precipitation Mode Rankings – Barrel/Baffle Region
1.	This mode of precipitation is ranked H as local concentration may reach super-saturation due to evaporation.
2.	This mode of precipitation is ranked M for un-buffered boric acid as the local super-saturation level is not expected to be high enough to initiate precipitation before other modes such as those associated with heated or boiling surfaces. Buffered ranking is L due to higher solubility.
3.	Precipitation due to confinement effects are not expected to occur as the spacing between barrel/baffle structures is not small enough (in the absence of debris or precipitation).

Table 7-5a Precipitation Modes Impacting Regional Precipitation Limit – Core Support Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Precipitation on cooled surfaces, walls, and structures associated with local super-saturation and heterogeneous nucleation.	H	L	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	M	L	Same as Period 1c		Same as Period 1c	
a. Impact of surface/fluid temperatures on local super-saturation of solution.	H	M			H	M				
b. Impact of surface characteristics such as material and surface topology.	H	L			H	L				
2. Precipitation (crystalline solid) in bulk solution of unconfined fluid associated with super-saturation and heterogeneous nucleation (due to presence of impurities).	M	M			L					

Table 7-5b Rationale for Precipitation Mode Rankings – Core Support Region

1.	This mode of precipitation is ranked H for un-buffered boric acid as this was observed in the Boiling Channel Test and CE test. For buffered boric acid this mode is ranked M due to the much higher solubility.
2.	This mode of precipitation is ranked M for un-buffered boric acid as is not likely to occur before other modes of precipitation nor result in significant precipitation and growth such as associated with heterogeneous nucleation on walls and surfaces. The mode was not seen in the Boiling Channel Test and was not reported in BACCHUS, VEERA/REWET, and CE tests. Buffered ranking is L due to higher solubility.

Table 7-6a Precipitation Modes Impacting Regional Precipitation Limit – Lower Head Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Precipitation on cooled surfaces, walls, and structures associated with local super-saturation and heterogeneous nucleation.	H	L	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	M	L	Same as Period 1c		Same as Period 1c	
a. Impact of surface/fluid temperature on local super-saturation of solution.	H	M			H	M				
b. Impact of surface characteristics such as material and surface topology.	H	L			H	L				
2. Precipitation (crystalline solid) in bulk solution of unconfined fluid associated with super-saturation and heterogeneous nucleation (due to presence of impurities).	M	M			L					

Table 7-6b Rationale for Precipitation Mode Rankings – Lower Head Region

1.	This mode of precipitation is ranked H for un-buffered boric acid as this was observed in the Boiling Channel Test and CE test. For buffered boric acid this mode is ranked M due to the much higher solubility.
2.	This mode of precipitation is ranked M as is not likely to occur before other modes of precipitation nor result in significant precipitation and growth such as associated with heterogeneous nucleation on walls and surfaces. The mode was not seen in the Boiling Channel Test, even with relatively cool (~70F) solution injected into the lower region of channel, and was not reported in BACCHUS, VEERA/REWET, and CE tests. For buffered boric acid, this mode is ranked L due to the significantly higher solubility. This mode may be ranked higher if a significant volume of cold solution is injected into the lower head region.

Table 7-7a Precipitation Modes Impacting Regional Precipitation Limit – Down Comer Region										
	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
Phenomena Description	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Precipitation on cooled surfaces, walls, and structures associated with local super-saturation and heterogeneous nucleation.	M	L	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	L		Same as Period 1c		Same as Period 1c	

Table 7-7b Rationale for Precipitation Mode Rankings – Down Comer Region	
1.	This mode of precipitation is ranked M as transport of high concentration un-buffered boric acid to down comer region such as through hot leg gap is expected to be small. For buffered boric acid this mode is ranked L due to the much higher solubility.

Table 7-8a Precipitation Modes Impacting Regional Precipitation Limit – Hot Leg Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Precipitation on walls and structures associated with local super-saturation and heterogeneous nucleation.	L		Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	L		Same as Period 1c		Same as Period 1c	

Table 7-8b Rationale for Precipitation Modes – Hot Leg Region

1.	This mode is ranked L in the hot leg region as there are no heated or cooled surfaces to support initiation of precipitation before other regions.

<table>
<tr><th colspan="11">Table 7-9a Precipitation Modes Impacting Regional Precipitation Limit – Upper Plenum Region</th></tr>
<tr><th rowspan="4">Phenomena Description</th><th colspan="6">Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period</th><th colspan="2">Transition Period</th><th colspan="2">Convection Transport Dominated Period</th></tr>
<tr><th colspan="2">Period 1a</th><th colspan="2">Period 1b</th><th colspan="2">Period 1c</th><th colspan="2">Period 2</th><th colspan="2">Period 3</th></tr>
<tr><th colspan="2">Un-Buffered Boric Acid</th><th colspan="2">Un-Buffered/ Buffered Boric Acid</th><th colspan="6">Buffered Boric Acid</th></tr>
<tr><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th></tr>
<tr><td>1. Precipitation on walls and structures above two-phase mixture level associated with liquid film/droplet evaporation (non-boiling) and super-saturation.</td><td>H</td><td>L</td><td rowspan="7">Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)</td><td rowspan="7">Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)</td><td>H</td><td>L</td><td colspan="2" rowspan="7">Same as Period 1c</td><td colspan="2" rowspan="7">Same as Period 1c</td></tr>
<tr><td>a. Impact of two-phase flow regime.</td><td>H</td><td>M</td><td>H</td><td>M</td></tr>
<tr><td>b. Impact of evaporation rate of solvent.</td><td>H</td><td>L</td><td>H</td><td>L</td></tr>
<tr><td>c. Impact of surface characteristics such as material and surface topology.</td><td>H</td><td>L</td><td>H</td><td>L</td></tr>
<tr><td>2. Precipitation on walls and structures associated with local super-saturation and heterogeneous nucleation.</td><td>M</td><td>L</td><td>L</td><td></td></tr>
<tr><td>3. Precipitation (crystalline solid) in bulk solution of unconfined fluid associated with super-saturation and heterogeneous nucleation (due to presence of impurities).</td><td>M</td><td>M</td><td>L</td><td></td></tr>
<tr><td>4. Precipitation associated with liquid solution confinement within small channels.</td><td>L</td><td></td><td>L</td><td></td></tr>
</table>

Table 7-9b	Rationale for Precipitation Mode Rankings – Upper Plenum Region
1.	Precipitation on evaporating surfaces above two-phase mixture level associated with liquid film/droplet evaporation and super-saturation is ranked H as this mode does not require a high bulk concentration to reach local super-saturation due to the evaporation from surfaces. This precipitation mode was observed in the Boiling Channel tests and reported in VEERA/REWET tests.
2.	This mode of precipitation is ranked M for un-buffered boric acid as local concentration may increase due to high concentration liquid transported from core boiling region to upper plenum with limited circulation between upper plenum and core regions. This mode is ranked L for buffered due to significant increase in solubility associated with buffered boric acid.
3.	This mode of precipitation is ranked M as is not likely to occur before other modes of precipitation nor result in significant precipitation and growth such as associated with heterogeneous nucleation on walls and surfaces. The mode was not seen in the Boiling Channel Test and was not reported in BACCHUS, VEERA/REWET, and CE tests. For buffered boric acid, this mode is ranked L due to the significantly higher solubility.
4.	Precipitation due to confinement effects are not expected to occur as the spacing between fuel rods is not small enough (in the absence of debris or precipitation).

Table 7-10a Precipitation Modes Impacting Regional Precipitation Limit – Steam Generator Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Precipitation (amorphous solid with voids) associated with rapid evaporation (boiling) and super-saturation of entrained liquid solution on heated surfaces above two-phase mixture level.	H	L	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	Use more limiting ranking from un-buffered (Period 1a) or buffered (Period 1c – 3)	H	L	Same as Period 1c		Same as Period 1c	
a. Impact of two-phase flow regime on liquid solution entrainment/de-entrainment to/from surface.	H	M			H	M				
b. Impact of surface/fluid temperature/heat flux on evaporation rate of solvent.	H	M			H	M				
c. Impact of heated surface characteristics such as material and surface topology.	H	L			H	L				
2. Precipitation (crystalline solid) of entrained liquid solution above two-phase mixture level on cooled or condensing surfaces.	M	L			M	L				
3. Precipitation associated with liquid solution confinement within small channels.	L				L					

Table 7-10b	Rationale for Precipitation Modes – Steam Generator Region
1.	Precipitation associated with entrained liquid solution is ranked H as it may occur well before the bulk solution reaches super-saturation in the reactor vessel. Steam generator is acting as a heat source (at least initially in post-LOCA conditions) during this precipitation mode.
2.	This mode of precipitation was observed in the Boiling Channel Test however in very small quantity compared to other modes of precipitation.
3.	Precipitation due to confinement effects are not expected to occur as diameter of the steam generator tubes is not small enough (in the absence of debris or precipitation).

7.5 SUMMARY OF HIGH RANKED PRECIPITATION MODES

The high-ranked precipitation modes involve interaction between buffered/un-buffered boric acid solution and various surfaces within the reactor vessel where super-saturation and favorable surface energy conditions exist for precipitation (to bring the system to a lower Gibbs free energy state). Local or regional super-saturation is likely to be brought about via heated or cooled surfaces to initiate sustainable nucleation and growth. Hence, based upon the Precipitation Modes PIRT review process, the following is a summary of the high ranked modes for initiation of boric acid (buffered or un-buffered) precipitation:

- Precipitation (amorphous solid with voids) associated with rapid evaporation (boiling) and super-saturation of entrained liquid solution on heated surfaces above two-phase mixture level (Core Boiling Region during Core Uncovery Only and Steam Generator Region).

- Precipitation on boiling surfaces in high void, two-phase region associated with bubble film (micro-layer film at base of bubble) evaporation and super-saturation (Core Boiling Region).

- Precipitation on walls and structures above two-phase mixture level associated with liquid film/droplet evaporation (non-boiling) and super-saturation (Core Boiling Region during Core Uncovery Only, Upper Plenum Region, Barrel/Baffle Region during Core Uncovery Only).

- Precipitation on cooled surfaces or walls and structures within single phase liquid region associated with local super-saturation and heterogeneous nucleation (Lower Head Region and Core Support Region).

These high-ranked precipitation modes are consistent with Boiling Channel Test experience as well as results in VEERA/REWET tests and CE test as reported, respectively, in the following:

- "...crystallization conditions in the system were achieved in three ways. In experiments with a constant pressure, crystallization started after several hours of boiling at the core top near the collapsed water level. In the experiments where super-saturation was reached by a fast reduction of the primary system pressure, crystallization took place in the whole upper part of the core section. In the third case crystallization was observed to take place in the lower plenum" (Reference 13, p.222).

- Boric acid precipitation in a PWR reactor vessel "...is a time dependent effect throughout the upper and lower portions of the vessel with the buildup proceeding gradually" (Reference 14, p. 4).

The BACCHUS tests did not report the occurrence of precipitation, however, it should be noted that these tests were not conducted with the objective of discovering or investigating precipitation modes.

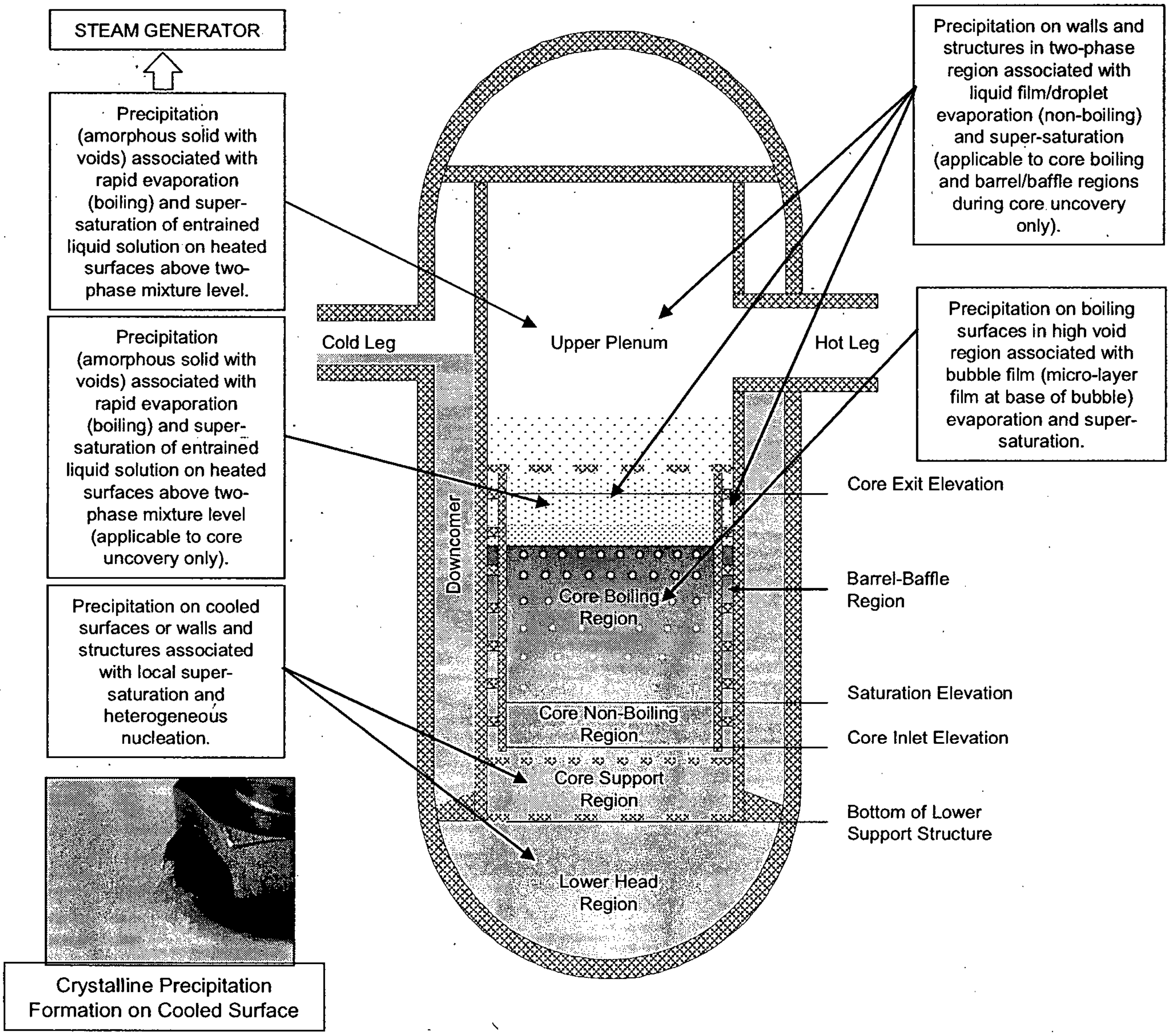

Figure 7-1 High-Ranked Un-Buffered Boric Acid Precipitation Modes

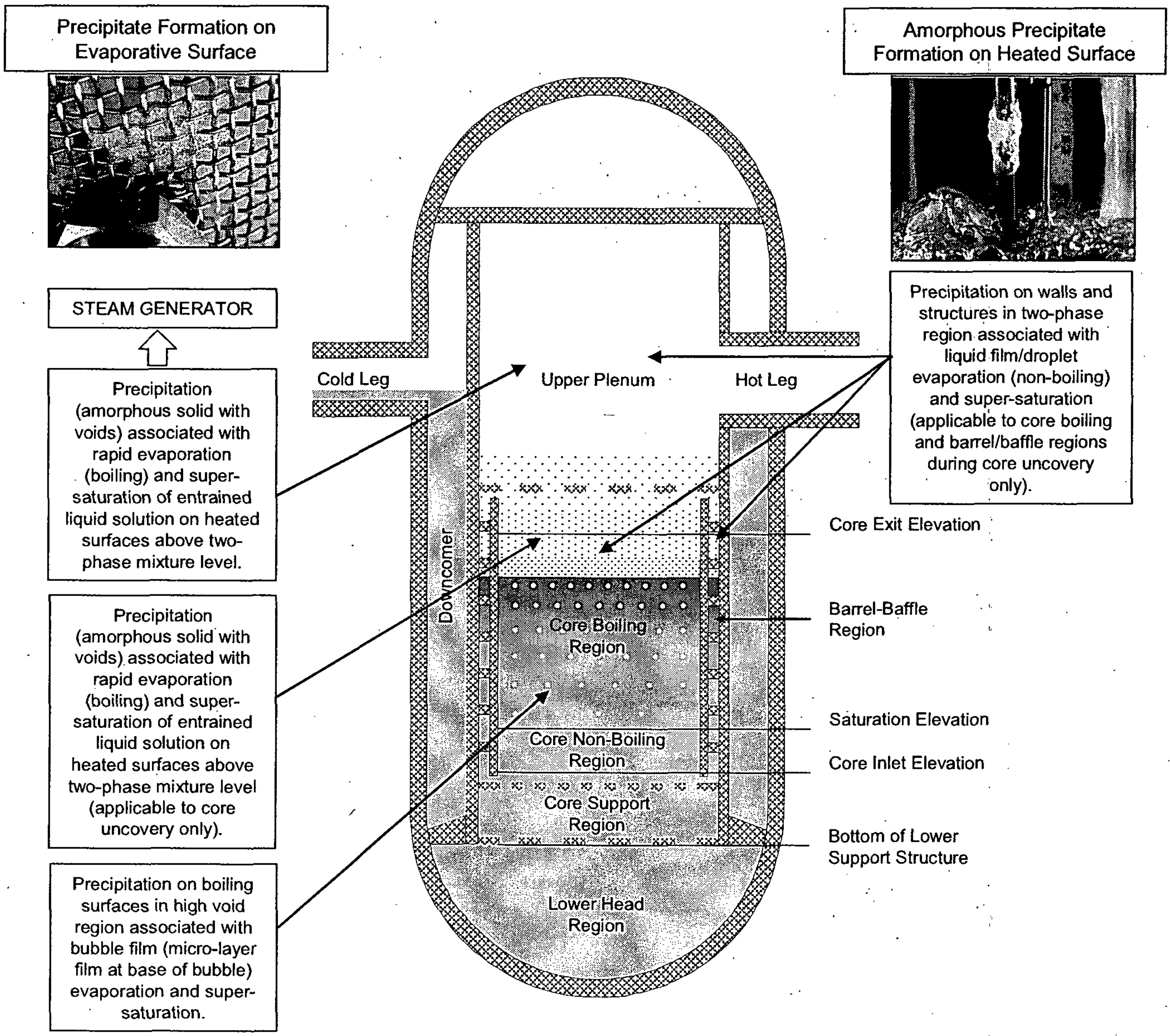

Figure 7-2 High-Ranked Buffered Boric Acid Precipitation Modes

7.6 STATE OF KNOWLEDGE OF HIGH RANKED PRECIPITATION MODES

All of the high ranked modes of precipitation expected in a reactor vessel involve interaction between the buffered/un-buffered boric acid solution and various surfaces within the reactor vessel (i.e. fuel rods, lower internal structures, and vessel walls). The state of knowledge of the high-ranked precipitation modes is generally low due to the lack of knowledge of the impact of reactor vessel materials and surface topology on nucleation and sustained growth of precipitate. Knowledge of bulk chemical solution behavior is important but not sufficient in itself to predict precipitation behavior in a reactor vessel. Due to the complex nature of the high-ranked precipitation phenomenon (nucleation and sustained net growth), improving the state of knowledge through testing (using prototypic materials, surface topology, and chemical solution properties and super-saturation levels) is recommended.

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8 PIRT FOR TRANSPORT AND MIXING OF UN-BUFFERED AND BUFFERED BORIC ACID

8.1 PURPOSE AND SCOPE OF TRANSPORT AND MIXING PIRT

The primary purpose and scope of this PIRT is to identify and rank phenomena that impact transport and mixing in the reactor vessel prior to precipitation as initiation of active dilution measures during post-LOCA long-term cooling is expected to preclude precipitation.

8.2 FIGURE OF MERIT: TRANSPORT AND MIXING

Figure of Merit: Transport and Mixing
Un-Buffered or Buffered Boric Acid Concentration in the Reactor Vessel Liquid Mixing Volume Relative to the Solubility Limit

PIRT rankings reflect relative importance of mixing and transport phenomena with respect to their impact on the figure of merit; that being, concentration in the reactor vessel liquid mixing volume relative to the solubility limit.

8.3 MIXING AND TRANSPORT PIRT WITH RANKINGS AND RATIONALE

<table>
<tr><th colspan="11">Table 8-1a Rankings for Core – Boiling (Decay Heat) Region</th></tr>
<tr><th rowspan="4">Phenomena Description</th><th colspan="6">Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period</th><th colspan="2">Transition Period</th><th colspan="2">Convection Transport Dominated Period</th></tr>
<tr><th colspan="2">Period 1a</th><th colspan="2">Period 1b</th><th colspan="2">Period 1c</th><th colspan="2">Period 2</th><th colspan="2">Period 3</th></tr>
<tr><th colspan="2">Un-Buffered Boric Acid</th><th colspan="2">Un-Buffered/ Buffered Boric Acid</th><th colspan="6">Buffered Boric Acid</th></tr>
<tr><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th></tr>
<tr><td>1. Bulk accumulation of solute in liquid mixing volume due to decay heat boil-off of liquid mixing volume.</td><td>M</td><td></td><td colspan="2" rowspan="7">Same as Period 1a</td><td colspan="2" rowspan="7">Same as Period 1a</td><td>H</td><td></td><td>H</td><td></td></tr>
<tr><td>a. Impact of liquid mixing volume size on accumulation of solute.</td><td>M</td><td>M</td><td>H</td><td>L</td><td>H</td><td>L</td></tr>
<tr><td>2. Turbulent transport/mixing (convection/dispersion) due to void (i.e., vapor phase) motion and power distribution within core boiling region.</td><td>H</td><td></td><td>H</td><td></td><td>H</td><td></td></tr>
<tr><td>a. Impact of two-phase flow regime associated with void motion.</td><td>H</td><td>M</td><td>H</td><td>M</td><td>H</td><td>M</td></tr>
<tr><td>b. Impact of decay heat boiling on void generation, size, and population.</td><td>H</td><td>M</td><td>H</td><td>M</td><td>H</td><td>M</td></tr>
<tr><td>c. Impact of radial/axial power distribution on void distribution (chimney effect).</td><td>H</td><td>M</td><td>H</td><td>M</td><td>H</td><td>M</td></tr>
<tr><td>d. Impact of interfacial drag between on transport of solution.</td><td>M</td><td>M</td><td>M</td><td>M</td><td>M</td><td>M</td></tr>
</table>

Table 8-1a (cont.) Rankings for Core – Boiling (Decay Heat) Region										
Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
e. Impact of geometry such as fuel lattices or fuel assembly gaps on void motion induced mixing/circulation.	M	M	Same as Period 1a		Same as Period 1a		M	M	M	M
f. Impact of turbulent mixing generated in wake region of moving void.	M	M					M	M	M	M
g. Impact of turbulence generated from chaotic boiling.	H	M					H	M	H	M
h. Impact of turbulence generated from flow across fuel assemblies and associated structures such as grids (vortex shedding, shear flow instability, flow separation).	M	M					H	M	H	M
3. Transport due to circulation/communication between core and upper plenum regions of liquid mixing volume.	H						H		H	
a. Impact of liquid entrainment/de-entrainment including pool type liquid entrainment and liquid film-type entrainment from solid surfaces.	H	L					H	L	H	L

Table 8-1a (cont.) Rankings for Core – Boiling (Decay Heat) Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
b. Impact of two-phase mixture level swell.	H	M	Same as Period 1a		Same as Period 1a		H	M	H	M
c. Impact of flooding/Counter Current Flow Limitation (CCFL) at upper core plate on liquid circulation/communication.	H	L					L	L	L	L
d. Impact of "chimney effect" from hot channel on circulation pattern.	H	M					H	M	H	M
e. Impact of two-phase flow regime on circulation/communication.	H	M					H	M	H	M
4. Molecular diffusion transport between liquid and vapor phases.	L						L		L	
5. Transport/mixing of between core region and other reactor vessel regions due to double diffusive convection.	L						L		L	

Table 8-1a (cont.) Rankings for Core – Boiling (Decay Heat) Region										
	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
Phenomena Description	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
6. Molecular diffusion transport within liquid mixing volume of core boiling region.	L		Same as Period 1a		Same as Period 1a		L		L –	
7. Molecular diffusion transport from core boiling region to barrel/baffle region.	L						L		L	
8. Natural convection transport of higher concentration solution from core region to other regions of reactor vessel where concentration is lower (fluid density instability type convection driven by concentration gradient in reactor vessel analogous to Rayleigh-Bénard convection).	L						M		H	
a. Impact of hydraulic resistance.	L						M	M	H	M
b. Impact of convection pattern or regime (steady roll cell, unsteady or intermittent roll cell, turbulent).	L						M	M	H	M
c. Impact of reactor vessel concentration gradient relative to temperature gradient on fluid density instability driven convection.	L						L		L	

Table 8-1a Rankings for Core – Boiling (Decay Heat) Region (cont.)

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
9. Transport/mixing within core region due to secondary flows induced by non-uniform wall turbulence or flow separation.	L		Same as Period 1a		Same as Period 1a		L		L	
10. Accumulation of solute due to boiling from metal heat and stored energy in the fuel.	L						N/A		N/A	
11. Accumulation of solute due to flashing (SBLOCA depressurization).	L						L		L	
12. Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel / loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	H						M		N/A	
a. Impact of coupling due to unsteady liquid entrainment from the core region into the steam generator to increase the steam binding effects which leads to flow oscillations and a net flow through the system.	H	L					M	L	N/A	
b. Impact of hydraulic resistance, inertance, and capacitance of boiling region on system stability.	H	M					M	M	N/A	

Table 8-1b	Rationale for Core – Boiling (Decay Heat) Region
1.	Decay heat boiling is the primary phenomenon that leads to increase in the liquid mixing volume concentration as un-buffered or buffered boric acid is not very miscible in steam at low pressure. Decay heat boil-off is ranked medium for period 1 as it is not expected that solute will accumulate significantly relative to the solubility limit. Decay heat boil-off is ranked high for later periods as it is expected that the solute will accumulate significantly relative to the solubility limit. a. The concentration of the solution is directly related to the size of the liquid mixing volume.
2.	Turbulent transport/mixing (convection/dispersion) due to void (i.e., vapor phase) motion within the core region is ranked high overall as it represents the primary phenomena responsible for transport/mixing within the core boiling region. a. High importance as the two-phase flow regime (i.e., bubbly, slug, churn, etc.) is directly related to motion of the vapor phase. b. High importance since decay heat drives the boiling process which impacts void formation and motion. c. High importance due to impact of void distribution and chimney effect on liquid flow pattern (i.e., increased void generation at lower elevation influences more of the liquid circulation region as opposed to a top-skewed power distribution). d. Moderate importance due to influence of interfacial drag (between liquid and vapor phases) on distribution of solute within liquid mixing volume (i.e., interfacial drag of lower concentration liquid to region of higher concentration as void moves upward in core boiling region). e. Moderate importance due to influence of geometry on void motion as it influences circulation and distribution of solute. f. Moderate importance as turbulence generated in wake of void induces mixing and circulation. g. High importance as chaotic boiling generates significant turbulence and mixing. h. Important since high turbulence levels can be generated from vortex shedding, flow separation, and shear flow instability especially in the presence of chaotic boiling.

Table 8-1b (cont.)	Rationale for Core – Boiling (Decay Heat) Region
3.	Transport due to circulation/communication between core and upper plenum regions of liquid mixing volume is considered a high-ranked phenomenon since it is the primary phenomenon by which higher concentration solution from core region liquid mixing volume is "diluted" with liquid mixing volume in upper plenum region. a. High importance as liquid entrainment provides primary means of communication between core and upper plenum liquid mixing volumes when two-phase mixture level is low or high void fraction exists in upper region of core. b. Two-phase mixture level swell is important as it impacts liquid mixing volume in core and upper plenum regions. c. Counter current flow at upper core plate is expected to have an important impact on liquid flow back into core region early as steam velocity is high; low importance later as steam velocity decreases with decay heat level. d. "Chimney effect" is expected to have an important effect on circulation pattern on flow to and from core region although not quite as much impact as two-phase flow regime, mixture level, or entrainment/de-entrainment. e. Two-phase flow regime is ranked high since flow path between core and upper plenum liquid mixing volumes is primarily two-phase.
4.	Low importance since un-buffered and buffered boric acid is not very miscible in steam at low pressure.
5.	Low importance due to weaker transport/mixing mechanism compared to Rayleigh-Benard type density-driven convection mechanisms.
6.	Low importance due to extremely weak transport/mixing mechanism compared to boiling/bubble motion, turbulence, entrainment, and density-driven convection mechanisms.
7.	Low importance due to extremely weak transport/mixing mechanism compared to density-driven convection mechanisms.
8.	Natural convection driven by concentration gradient (analogous to Rayleigh-Benard convection) is ranked high in later period as it is expected to have important impact on transport in reactor vessel liquid mixing volume. a. Importance of hydraulic resistance increases as concentration gradient increases. b. Convection pattern is important as it impacts effectiveness of transport/mixing. c. Concentration gradient relative to temperature gradient is of low importance in core region as temperature difference is small in boiling region (saturated conditions).
9.	Low ranking as secondary flow not as effective as turbulent mixing and mixing is usually confined to secondary flow region itself whereas turbulence is expected to diffuse beyond region of turbulence generation.
10.	Low importance early as metal heat from structures and stored energy from fuel may cause localized boiling hence accumulation/build-up of un-buffered and buffered boric acid; N/A later on because metal heat and stored energy from fuel has been released.

Table 8-1b (cont.)	Rationale for Core – Boiling (Decay Heat) Region
11.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.
12.	Higher importance early because there can be higher net flows through the reactor system which would cause more mixing and entrainment. a. Higher importance early on as entrainment is higher due to higher gas velocity. Importance diminishes with time as decay heat hence, gas velocity, decreases. b. Higher importance early on as pressure drop is higher due to higher gas velocity. Importance diminishes with time as decay heat hence, pressure drop, decreases.

Table 8-2a Rankings for Core – Non-Boiling Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Natural circulation transport within core region due to "chimney effect" of hot channel.	H		Same as Period 1a		Same as Period 1a		H		H	
a. Impact of hydraulic resistance.	H	M					H	M	H	M
b. Impact of circulation pattern.	M	M					H	M	H	M
2. Natural convection transport of higher concentration solution from core region to other regions of reactor vessel where concentration is lower (fluid density instability type convection driven by concentration gradient in reactor vessel analogous to Rayleigh-Benard convection).	L						M		H	
a. Impact of hydraulic resistance.	L	M					M	M	H	M
b. Impact of convection pattern or regime (steady roll cell, unsteady or intermittent roll cell, turbulent).	L	M					M	M	H	M

<table>
<tr><td colspan="11">Table 8-2a (cont.) Rankings for Core – Non-Boiling Region</td></tr>
<tr><td rowspan="4">Phenomena Description</td><td colspan="6">Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period</td><td colspan="2">Transition Period</td><td colspan="2">Convection Transport Dominated Period</td></tr>
<tr><td colspan="2">Period 1a</td><td colspan="2">Period 1b</td><td colspan="2">Period 1c</td><td colspan="2">Period 2</td><td colspan="2">Period 3</td></tr>
<tr><td colspan="2">Un-Buffered Boric Acid</td><td colspan="2">Un-Buffered/ Buffered Boric Acid</td><td colspan="6">Buffered Boric Acid</td></tr>
<tr><td>Rank</td><td>SOK</td><td>Rank</td><td>SOK</td><td>Rank</td><td>SOK</td><td>Rank</td><td>SOK</td><td>Rank</td><td>SOK</td></tr>
<tr><td>c. Impact of reactor vessel concentration gradient relative to temperature gradient on fluid density instability driven convection.</td><td>L</td><td>L</td><td colspan="2" rowspan="6">Same as Period 1a</td><td colspan="2" rowspan="6">Same as Period 1a</td><td>M</td><td>L</td><td>H</td><td>L</td></tr>
<tr><td>3. Turbulent transport (dispersion) within core region.</td><td>H</td><td></td><td>H</td><td></td><td>H</td><td></td></tr>
<tr><td>a. Impact of turbulence generated from flow (vortex shedding, shear instability, flow separation) across fuel assemblies and associated structures such as grids.</td><td>H</td><td>M</td><td>H</td><td>M</td><td>H</td><td>M</td></tr>
<tr><td>4. Transport/mixing within core region due to secondary flows induced by non-uniform wall turbulence or flow separation.</td><td>M</td><td></td><td>M</td><td></td><td>M</td><td></td></tr>
<tr><td>a. Impact of non-axisymmetrical fuel assembly geometry on wall turbulence and hence secondary flows.</td><td>M</td><td>M</td><td>M</td><td>M</td><td>M</td><td>M</td></tr>
<tr><td>5. Double diffusive convection transport.</td><td>L</td><td></td><td>M</td><td>L</td><td>L</td><td></td></tr>
</table>

Table 8-2a (cont.) Rankings for Core – Non-Boiling Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
a. Impact of fuel assemblies and structures on molecular diffusion in radial/lateral direction. Rate of molecular diffusion relative to thermal diffusion in fluid in radial/lateral direction impacts double diffusive convection in core region.	L		Same as Period 1a		Same as Period 1a		M	L	L	
b. Impact of turbulent dispersion in radial/lateral direction.	L						M	L	L	
c. Impact of structure metal heat on thermal diffusion in fluid in radial/lateral direction.	L						M	L	L	
d. Impact of fuel assembly and structures on axial hydraulic resistance/drag with respect to double diffusive convection in axial/vertical direction.	L						M	L	L	
e. Impact of convection pattern (i.e., salt fingers, diffusive layers, etc.) on transport.	L						M	L	L	

Table 8-2a (cont.) Rankings for Core – Non-Boiling Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
f. Impact of temperature gradient and concentration gradient.	L		Same as Period 1a		Same as Period 1a		M	L	L	
g. Impact of axial/radial power distribution on temperature/concentration gradients in core.	L						M	L	L	
6. Molecular diffusion transport from boiling region of core to non-boiling region.	L						L		L	
7. Molecular diffusion transport from non-boiling core region to barrel/baffle region.	L						L		L	
8. Accumulation of solute due to boiling from metal heat and stored energy in the fuel.	L						N/A		N/A	
9. Accumulation of solute due to flashing (SBLOCA depressurization).	L						L		L	

Table 8-2a (cont.) Rankings for Core – Non-Boiling Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
10. Transport/mixing due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	H		Same as Period 1a		Same as Period 1a		M		N/A	
a. Impact of hydraulic resistance, inertance, and capacitance of non-boiling region on system stability.	H	M	Same as Period 1a		Same as Period 1a		M	M	N/A	

Table 8-2b	Rationale for Core – Non-Boiling Region
1.	"Chimney effect" is of high importance as it is expected to have a strong impact on natural circulation transport in non-boiling region of core. a. High importance since drag/resistance impacts convection velocity. b. High importance since circulation pattern determines extent of convection transport.
2.	Natural convection driven by concentration impact on fluid density increases in importance as the concentration gradients increase within the core region. a. Hydraulic resistance becomes more important as concentration-driven convection increases in importance. b. Flow regime determines strength of convection transport. Its importance increases as the concentration increases later in time and this mode of convection becomes stronger. c. The impact of concentration gradient relative to temperature gradient becomes more important as concentration increases.
3.	Turbulence is of high importance as is it is a very highly effective mixing/transport phenomenon. a. High importance due to level of turbulence intensity expected from turbulent flow through complex core geometry.
4.	Secondary flows are given a moderate ranking as they are not quite as effective as turbulent mixing and mixing is usually confined to secondary flow region itself whereas turbulence is expected to diffuse beyond region of turbulence generation. a. Moderate importance since secondary flows are not expected to be quite as effective as turbulent mixing.

Table 8-2b (cont.)	Rationale for Core – Non-Boiling Region
5.	Low importance early since concentration gradient is not expected to be sufficient to initiate convection and much weaker mixing/transport mechanism compared to turbulent/unsteady flow. Moderate importance is expected in transition period as conditions are expected to be more favorable for this transport phenomenon. Low importance later on due to being a weaker transport/mixing mechanism compared to Rayleigh-Benard type density-driven convection mechanisms. b. Moderate importance in transition period as turbulent dispersion will disrupt/prevent onset of double diffusive convection. c. Moderate importance in transition period as vertical structures/channels may restrict molecular diffusion thus enhancing double diffusive convection. d. Moderate importance in transition period as radial/lateral thermal diffusion from structures would degrade double diffusive convection. e. Moderate importance in transition period hydraulic resistance impacts length scale over which this transport mechanism is effective. f. Moderate importance in transition period since complex geometry will be more conducive to convection patterns of a specific L/D. g. Moderate importance in transition period as steepness of gradient impacts length scale over which this transport mechanism is effective. h. Moderate importance in transition period as thermal and concentration gradients will impact effectiveness of this transport mechanism.
6.	Low importance due to extremely weak transport/mixing mechanism compared to turbulence and density-driven convection mechanisms.
7.	Low importance due to extremely weak transport/mixing mechanism compared to turbulence and density-driven convection mechanisms.
8.	Low importance early as metal heat from structures and stored energy from fuel may cause some localized boiling hence accumulation/build-up of solute; N/A later on because metal heat and stored energy from fuel has been released.
9.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.
10.	Higher importance in period 1 because there can be higher net flows through the reactor system which would cause more mixing. a. Higher importance early on as pressure drop is higher due to higher velocity. Importance diminishes with time as decay heat hence, pressure drop, decreases.

Table 8-3a Rankings for Core Support Region (Bottom of Active Fuel to Bottom of Core Support Plate)

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Molecular diffusion transport between core and lower plenum regions.	L		Same as Period 1a		Same as Period 1a		L		L	
2. Natural convection (due to concentration driven fluid density in stability analogous to Rayleigh-Benard convection) transport of higher concentration solution between core region and lower head region liquid mixing volume where concentration is lower.	L						M		H	
a. Impact of lower core support plate hole geometry.	L	M					M	L	H	L
b. Impact of reactor vessel concentration gradient relative to temperature gradient on fluid density instability driven convection.	L	L					M	L	H	L

Table 8-3a (cont.) Rankings for Core Support Region (Bottom of Active Fuel to Bottom of Core Support Plate)

	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
Phenomena Description	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
3. Double-diffusive convection transport.	L		Same as Period 1a		Same as Period 1a		M	L	L	
a. Impact of structures on molecular diffusion in radial/lateral direction.	L						M	L	L	
b. Impact of turbulent dispersion in radial/lateral direction; it may degrade or delay onset of double diffusive convection.	L						M	L	L	
c. Impact of structure metal heat on thermal diffusion in fluid in radial/lateral direction.	L						L	L	L	
d. Impact of structures on axial hydraulic resistance/drag with respect to double diffusive convection in axial/vertical direction.	L						M	L	L	

Table 8-3a (cont.) Rankings for Core Support Region (Bottom of Active Fuel to Bottom of Core Support Plate)

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
e. Impact of convection pattern (i.e., salt fingers, diffusive layers, etc.) on transport.	L						M	L	L	
f. Impact of temperature gradient and concentration gradient.	L						M	L	L	
4. Accumulation of solute due to boiling (metal heat release) from structures.	M	M	Same as Period 1a		Same as Period 1a		L		N/A	
5. Accumulation of solute due to flashing (SBLOCA depressurization).	L						L		L	
6. Turbulent transport (dispersion) within core support region associated with convection in reactor vessel.	L						M		H	
a. Impact of turbulence generated from flow (vortex shedding, shear instability) across structures.	L	M					M	M	H	M
7. Transport due to	H		s P e r i		s P e r i		H		H	

Table 8-3a (cont.) Rankings for Core Support Region (Bottom of Active Fuel to Bottom of Core Support Plate)

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
circulation/communication between core support and core regions of liquid mixing volume.										
a. Impact of "chimney effect" from hot channel on circulation pattern.	H	H					H	H	H	H
8. Transport/mixing due to unsteady oscillatory flow resulting from reactor vessel / loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	H						M		N/A	
a. Impact of hydraulic resistance, inertance, and capacitance on system stability.	H	M					M	M	N/A	

Table 8-3b	Rationale for Core Support Region (Bottom of Active Fuel to Bottom of Core Support Plate)
1.	Low importance early due to low concentration difference in reactor vessel. Low importance later due to molecular diffusion being a weak transport/mixing mechanism compared to turbulence and density-driven convection phenomena.
2.	Natural convection driven by concentration impact on fluid density increases in importance as the concentration gradients increase within the core support region. a. Low importance early due to low concentration difference; more important later as concentration increases leading to density-driven convection as hole geometry influences convection pattern. b. Low importance early due to low concentration difference; more important later as concentration increases.
3.	Low importance early since concentration gradient is not expected to be sufficient to initiate convection and much weaker mixing/transport mechanism compared to turbulent/unsteady flow. Moderate importance in transition period as conditions are expected to be favorable for this transport phenomenon. Low importance later on due to being a weaker transport/mixing mechanism compared to Rayleigh-Benard type density-driven convection mechanisms. a. Moderate importance in transition period as vertical structures/channels may restrict molecular diffusion thus enhancing double diffusive convection. b. Moderate importance in transition period as turbulent dispersion will disrupt/prevent onset of double diffusive convection. c. Moderate importance in transition period as radial/lateral thermal diffusion from structures would degrade double diffusive convection d. Moderate importance in transition period hydraulic resistance impacts length scale over which this transport mechanism is effective. e. Moderate importance in transition period as steepness of gradient impacts length scale over which this transport mechanism is effective. f. Moderate importance in transition period as thermal and concentration gradients will impact effectiveness of this transport mechanism.
4.	Moderate importance early as metal heat from structures may cause localized boiling hence accumulation/build-up of solute; low importance and N/A later on because heat already removed.
5.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.
6.	Turbulence becomes high ranked as concentration related convection increases in this region and it is very highly effective mixing/transport phenomenon. a. Low importance early since low concentration is expected in this region; becomes more important as concentration increases later in transient.

Table 8-3b (cont.)	Rationale for Core Support Region (Bottom of Active Fuel to Bottom of Core Support Plate)
7.	Transport due to circulation/communication between core support and core regions of liquid mixing volume is considered a high-ranked phenomenon since it is close to and in good communication with core region. a. "Chimney effect" is expected to important effect on circulation pattern on flow to and from core region.
8.	Higher importance in period 1 because there can be higher net flows through the reactor system which would cause more mixing. a. Higher importance early on as pressure drop is higher due to higher velocity. Importance diminishes with time as decay heat hence, pressure drop, decreases.

<table>
<tr><th colspan="11">Table 8-4a Rankings for Lower Head Region</th></tr>
<tr><th rowspan="4">Phenomena Description</th><th colspan="6">Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period</th><th colspan="2">Transition Period</th><th colspan="2">Convection Transport Dominated Period</th></tr>
<tr><th colspan="2">Period 1a</th><th colspan="2">Period 1b</th><th colspan="2">Period 1c</th><th colspan="2">Period 2</th><th colspan="2">Period 3</th></tr>
<tr><th colspan="2">Un-Buffered Boric Acid</th><th colspan="2">Un-Buffered/ Buffered Boric Acid</th><th colspan="6">Buffered Boric Acid</th></tr>
<tr><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th></tr>
<tr><td>1. Natural convection (due to concentration driven fluid density instability analogous to Rayleigh-Benard convection) transport of higher concentration solution from core support region to lower head region liquid mixing volume.</td><td>L</td><td></td><td colspan="2" rowspan="4">Same as Period 1a</td><td colspan="2" rowspan="4">Same as Period 1a</td><td>M</td><td></td><td>H</td><td></td></tr>
<tr><td>a. Impact of lower head structures on hydraulic resistance.</td><td>L</td><td>M</td><td>M</td><td>M</td><td>H</td><td>M</td></tr>
<tr><td>b. Impact of reactor vessel concentration gradient relative to temperature gradient on fluid density instability driven convection.</td><td>L</td><td>L</td><td>M</td><td>L</td><td>H</td><td>L</td></tr>
<tr><td>2. Turbulent transport (dispersion) within lower head region associated with convection in reactor vessel.</td><td>L</td><td></td><td>M</td><td></td><td>H</td><td></td></tr>
</table>

Table 8-4a (cont.) Rankings for Lower Head Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
a. Impact of turbulence generated from flow (vortex shedding, shear instability) across lower plenum structures such as support columns, instrumentation tubes and flow skirts.	L	M	Same as Period 1a		Same as Period 1a		M	M	H	M
b. Impact of downcomer flow (velocity distribution and turbulence level) on turbulence within the lower head region.	L	M					L	M	L	M
3. Mixing of un-buffered and buffered solution within lower plenum due to secondary flow patterns within the lower head region.	L						L		N/A	
4. Molecular diffusion transport from core support to lower head region.	L						L		L	

Table 8-4a (cont.) Rankings for Lower Head Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
5. Accumulation of solute due to boiling (metal heat release) from lower head structures.	M	M	Same as Period 1a		Same as Period 1a		L		N/A	
6. Accumulation of solute due to flashing (SBLOCA depressurization).	L						L		L	
7. Double diffusive convection transport.	L						L		L	
8. Transport due to circulation/communication between core support and lower head regions of liquid mixing volume.	M	M					M	M	M	M
a. Impact of "chimney effect" from hot channel on circulation pattern.	M	M					M	M	M	M

Table 8-4a (cont.) Rankings for Lower Head Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
9. Transport/mixing due to unsteady or oscillatory flow resulting from reactor vessel / loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	H		Same as Period 1a		Same as Period 1a		M		N/A	
a. Impact of hydraulic resistance, inertance, and capacitance of lower head region on system stability.	H	M					M	M	N/A	

Table 8-4b	Rationale for Lower Head Region
1.	Natural convection (analogous to Rayleigh-Benard convection) driven by concentration increases in importance as the concentration gradients increase within the reactor vessel. a. Low importance early due to low concentration difference; high importance later as concentration increases leading to density-driven convection as lower head structure geometry influences convection pattern. b. Low importance early due to small concentration gradient; importance increases as concentration gradient increases relative to temperature gradient and density instability leads to transport via natural convection analogous to Rayleigh-Benard convection.
2.	Turbulence becomes high ranked as concentration related convection increases in this region and it is very highly effective mixing/transport phenomenon. a. Low importance early due to low concentration; importance increases as solute is transported from core and support region to lower head region. b. Low importance as lower head structure geometry influences flow pattern.
3.	Low importance due to expected dominance of concentration-driven convection and turbulent dispersion.
4.	Low importance as concentration-driven convection (analogous to Rayleigh-Benard convection) and turbulent dispersion transport will dominate over molecular diffusion.
5.	Importance diminishes as metal heat from structures is released; N/A later on because metal heat has been released.
6.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.
7.	Low importance early since concentration gradient is not expected to be sufficient to initiate convection. Low importance later on due to being a weaker transport/mixing mechanism compared to Rayleigh-Benard type density-driven convection mechanisms.
8.	Transport due to circulation/communication between lower head and core support regions of liquid mixing volume is considered a medium ranked phenomenon since it is expected to occur but not as strongly as in core or core support regions. a. “Chimney effect” is expected to have some effect on circulation pattern.
9.	Higher importance in period 1 because there can be higher net flows through the reactor system which would cause mixing. a. Higher importance early on as pressure drop is higher due to higher velocity. Importance diminishes with time as decay heat hence, pressure drop, decreases.

Table 8-5a Rankings for Barrel/Baffle Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Natural convection transport due to concentration gradient from core region to barrel/baffle region via top, intermediate (at pressure relief holes), or bottom flow gaps.	M		Same as Period 1a		Same as Period 1a		H		H	
a. Impact of presence of holes.	M	M					H	M	H	M
b. Impact of gap/hole/former hydraulic resistance.	M	L					H	L	H	L
c. Impact of fluid temperature gradient on concentration-driven convection.	L	L					L	L	L	L
2. Turbulent transport/mixing between former elevations.	L						L		L	
3. Molecular diffusion transport within barrel/baffle region or between the core and barrel/baffle regions.	L						L		L	
4. Double diffusive convection transport.	L						L		L	

Table 8-5a Rankings for Barrel/Baffle Region (cont.)

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
5. Accumulation of solute due to boiling from metal heat.	M	M	—				L		N/A	
6. Accumulation of solute due to flashing (SBLOCA depressurization).	L						L		L	
7. Transport/mixing due to Chimney Effect.	L		Same as Period 1a		Same as Period 1a		L		L	
8. Transport/mixing due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	H						M		N/A	
a. Impact of hydraulic resistance, inertance, and capacitance of barrel/baffle region on system stability.	H	M					M	M	N/A	

Table 8-5b	Rationale for Barrel/Baffle Region
1.	Density-driven natural convection due to concentration impact on density is ranked medium to high as concentration increases in core region. a. High importance as the presence of holes is required for circulation transport to/from this region. Importance is moderate in early phase as the concentration gradient is not large to drive strong convection. b. Important as hydraulic resistance impacts the circulation rate and hence the transport of solute. c. Low importance as convection gradient is expected to dominate over temperature gradient with respect to convection.
2.	Low importance as circulation velocities and therefore turbulence is expected to be low.
3.	Low importance as transport by molecular diffusion is expected to be very weak compared to density-driven circulation.
4.	Low importance as transport by double diffusive convection is expected to be dominated by density-driven convection.
5.	Medium importance early as metal heat from structures that may cause localized boiling and hence accumulation/build-up solute; less important later on because metal heat has been released.
6.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.
7.	Transport due to circulation/communication between core and barrel/baffle regions of liquid mixing volume is considered a low ranked phenomenon since it is expected to occur but not as strong near peripheral region of core.
8.	Higher importance in period 1 because there can be higher net flows through the reactor system which would cause more uniform mixing. a. Higher importance early on as pressure drop is higher due to higher velocity. Importance diminishes with time as decay heat hence, pressure drop, decreases.

Table 8-6a Rankings for Upper Plenum Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Transport due to circulation/communication between upper plenum and hot leg regions of liquid mixing volume.	H		Same as Period 1a		Same as Period 1a		H		H	
a. Impact of liquid entrainment including pool type liquid entrainment (when two-phase mixture level is in upper plenum or liquid pool exists).	H	L					H	L	H	L
b. Impact of upper plenum structures such as guide tubes on de-entrainment of liquid.	M	L					M	L	M	L
c. Impact of two-phase flow regime and mixture level swell.	H	M					H	M	H	M
2. Molecular diffusion transport between liquid and vapor phases.	L						L		L	

Table 8-6a (cont.) Rankings for Upper Plenum Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
3. Turbulent transport/mixing within upper plenum region due to steam jetting and turbulence generated from upper plenum structure such as guide tubes.	M	M	Same as Period 1a		Same as Period 1a		M	M	M	M
4. Reduction of reactor vessel mixing volume due to increased pressured drop associated with deposition of solute due to boiling/evaporation from upper plenum structures.	M	L					M	L	M	L
5. Accumulation of solute due to flashing (SBLOCA depressurization).	M	L					M	L	M	L
6. Steady net liquid entrainment transport above two-phase mixture level in upper plenum/hot leg regions.	L						L		L	

Table 8-6a (cont.) Rankings for Upper Plenum Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
7. Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel / loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	H		Same as Period 1a		Same as Period 1a		M		N/A	
a. Impact of coupling due to unsteady liquid entrainment from upper plenum/hot leg into the steam generator to increase the steam binding effects which leads to flow oscillations and a net flow through the system.	H	L					M	L	N/A	
b. Impact of upper plenum level, hydraulic resistance, inertance, and capacitance on system stability.	H	M					H	M	N/A	

Table 8-6b Rationale for Upper Plenum Region

1.	High importance is given to transport between upper plenum and hot leg region due to circulation and mixing. a. High importance early due to decay higher steam velocity to entrain liquid. High importance later when 2-phase mixture level in upper plenum as entrainment of liquid is more likely. b. Moderate importance as tests (Dallman & Kirchner) shows significant de-entrainment across (several) guide tubes. c. Important as two-phase flow regime impacts level swell (direct communication) and entrainment/de-entrainment (indirect communication). Important as two-phase mixture level provides direct communication when mixture level is above bottom of hot leg and impacts entrainment when mixture level is below bottom of hot leg.
2.	Low importance since un-buffered and buffered boric acid is not very miscible in steam.
3.	Moderate importance as steam velocity in upper plenum and turbulence levels are expected to be lower than core region.
4.	Moderate importance as it is expected that some quantity of solute may be deposited on upper plenum structures.
5.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.
6.	Low importance as the amount of steady entrained liquid droplets above two-phase mixture level is expected to be small.
7.	Higher importance in period 1 because there can be higher net flows through the reactor system which would cause more mixing and entrainment. a. Higher importance early on as entrainment is higher due to higher gas velocity. Importance diminishes with time as decay heat hence, gas velocity, decreases. b. Higher importance early on as pressure drop is higher due to higher gas velocity. Importance diminishes with time as decay heat hence, pressure drop, decreases.

<table>
<tr><th colspan="11">Table 8-7a Rankings for Downcomer Region</th></tr>
<tr><th rowspan="4">Phenomena Description</th><th colspan="6">Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period</th><th colspan="2">Transition Period</th><th colspan="2">Convection Transport Dominated Period</th></tr>
<tr><th colspan="2">Period 1a</th><th colspan="2">Period 1b</th><th colspan="2">Period 1c</th><th colspan="2">Period 2</th><th colspan="2">Period 3</th></tr>
<tr><th colspan="2">Un-Buffered Boric Acid</th><th colspan="2">Un-Buffered/ Buffered Boric Acid</th><th colspan="6">Buffered Boric Acid</th></tr>
<tr><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th><th>Rank</th><th>SOK</th></tr>
<tr><td>1. Transport of lower concentration solution (in excess of make-up for boil-off) from downcomer to inner reactor vessel liquid mixing volume regions.</td><td>H</td><td></td><td colspan="2" rowspan="7">Same as Period 1a</td><td colspan="2" rowspan="7">Same as Period 1a</td><td>H</td><td></td><td>H</td><td></td></tr>
<tr><td>a. Impact of down comer gravity head on supplying liquid mixing volume.</td><td>H</td><td>H</td><td>H</td><td>H</td><td>H</td><td>H</td></tr>
<tr><td>b. Impact of Boric Acid Makeup Tank (BAMT) injection (CE only).</td><td>M</td><td>M</td><td>N/A</td><td></td><td>N/A</td><td></td></tr>
<tr><td>2. Accumulation of solute in liquid phase due to downcomer boiling.</td><td>M</td><td>M</td><td>N/A</td><td></td><td>N/A</td><td></td></tr>
<tr><td>3. Accumulation of solute due to flashing (SBLOCA depressurization).</td><td>L</td><td></td><td>L</td><td></td><td>L</td><td></td></tr>
<tr><td>4. Transport and generation of turbulence due to cold leg flow interaction with core barrel in down comer region as related to turbulent transport/mixing within lower plenum/core support regions.</td><td>L</td><td></td><td>L</td><td></td><td>L</td><td></td></tr>
</table>

Table 8-7a Rankings for Downcomer Region (cont.)

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
5. Transport and generation of secondary flow patterns within down comer as related to mixing in lower plenum/core support regions.	L		Same as Period 1a		Same as Period 1a		L		L	
6. Transport/mixing due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	H						M		N/A	
a. Impact of down comer level, hydraulic resistance, inertance, and capacitance on system stability.	H	M					M	M	N/A	

Table 8-7b Rationale for Downcomer Region

1.	The concentration of the make-up flow is initially higher for some ECCS designs. As the concentration increases in the lower plenum/core regions, the inflow of more dilute make-up flow from the downcomer promotes density-driven convection due to the concentration gradient in the reactor vessel. Excess make-up flow increases the liquid mixing volume in the inner reactor vessel. a. High importance as it influences rate at which make-up flow is transported to the core region. b. Moderately important early as this high concentration/low flow rate source will mix with lower concentration/high flow rate sources which provide make-up flow; N/A later since the BAMT will have emptied.
2.	Moderate importance early as metal heat from structures that may cause localized boiling and hence accumulation/build-up of solute is less important than that occurring in core region; N/A later on because metal heat has been released.
3.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.
4.	Low importance as turbulence level resulting from lower plenum structures is expected to be much more dominant relative to downcomer region.
5.	Low importance due to expected dominance of lower internals structures and turbulent dispersion relative to downcomer induced secondary flows on mixing/transport in reactor vessel liquid mixing volume.
6.	Higher importance in period 1 because there can be higher net flows through the reactor system which would cause more mixing. a. Higher importance early on as pressure drop is higher due to higher gas velocity. Importance diminishes with time as decay heat hence, pressure drop, decreases.

Table 8-8a Rankings for Hot Leg Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Transport due to circulation/communication between upper plenum and hot leg regions of liquid mixing volume.	H		Same as Period 1a		Same as Period 1a		H		H	
a. Impact of two-phase flow regime and mixture level swell.	H	M					H	M	H	M
b. Impact of liquid entrainment/de-entrainment and gravity drain back to upper plenum when mixture level in upper plenum is low.	H	L					H	L	H	L
2. Natural circulation of higher concentration solution from upper plenum/hot leg to other regions such as downcomer region via hot leg nozzle gap and/or RVVVs for B&W plants.	L						M		H	

Table 8-8a (cont.) Rankings for Hot Leg Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
a. Impact of differential expansion on hot leg gap flow path dimension.	L	M	Same as Period 1a		Same as Period 1a		M	M	H	M
b. Impact of gap hydraulic resistance.	L	M					M	M	H	M
3. Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel / loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	H						M		N/A	
a. Impact of coupling due to unsteady liquid entrainment from hot leg into the steam generator to increase the steam binding effects which leads to flow oscillations and a net flow through the system.	H	L					M	L	N/A	

Table 8-8a (cont.) Rankings for Hot Leg Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
b. Impact of coupling due to increased loop pressure drop due to high intermittent steam flow.	H	M	Same as Period 1a		Same as Period 1a		M	M	N/A	
c. Impact of hot leg hydraulic resistance, inertance, and capacitance on system stability.	H	M					M	M	N/A	
4. Steady net liquid entrainment transport above two-phase mixture level in the hot leg to steam generator.	L						L		L	

Table 8-8b	Rationale for Hot Leg Region
1.	Once the liquid flow between upper plenum and hot leg is no longer counter current flow limited, the liquid volume in the hot leg will communicate with the upper plenum thus expanding the liquid volume available for mixing. The communication can occur via two-phase mixture level swell or liquid entrainment/de-entrainment. a. High importance as flow regime impacts two-phase mixture level and entrainment/de-entrainment. Two-phase mixture level impacts liquid entrainment (indirect communication) when level is below hot leg and provides direct communication when level is above bottom of hot leg. b. Important as entrainment/de-entrainment is primary means of communication between liquid mixing volume of core/upper plenum region and liquid mixing volume of hot leg when two-phase mixture level is below hot leg elevation.
2.	Higher concentration solution can be transported out of the upper plenum/core region after the mixture level reaches the hot leg and/or RVVV elevation. a. Low importance early as the concentration is low; importance increases as the concentration increases. This is the primary mechanism for removing solute from liquid mixing volume. b. Low importance early as the concentration is low; importance increases as the concentration increases.
3.	Higher importance in the turbulent/unsteady and transition periods because there can be higher net flows through the reactor system which would cause more mixing and entrainment. a. Higher importance early on as entrainment is higher due to higher gas velocity. Importance diminishes with time as decay heat hence, gas velocity, decreases. b. Higher importance early on as pressure drop is higher due to higher gas velocity. Importance diminishes with time as decay heat hence, pressure drop, decreases. c. Higher importance early on as pressure drop is higher due to higher velocity. Importance diminishes with time as decay heat hence, pressure drop, decreases.
4.	Low importance as steady liquid entrainment is expected to be low.

Table 8-9a Rankings for Steam Generator Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Reduction of reactor vessel mixing volume due to increased pressure drop from solute deposition on steam generator tubes.	M	L	Same as Period 1a		Same as Period 1a		M	L	L	
2. Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel / loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	H						M		N/A	
a. Impact of coupling due to unsteady liquid entrainment into the steam generator to increase the steam binding effects which leads to flow oscillations and a net flow through the system.	H	L					M	L	N/A	

Table 8-9a (cont.) Rankings for Steam Generator Region										
	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
Phenomena Description	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
b. Impact of droplet carryover through steam generator.	H	L	Same as Period 1a		Same as Period 1a		M	L	L	L
c. Impact of steam generator hydraulic resistance, inertance, and capacitance on system stability.	H	M					M	M	N/A	
3. Steady, net liquid entrainment transport above two-phase mixture level into steam generator.	L						L		L	

Table 8-9b	Rationale for Steam Generator Region
1.	Medium importance as pressure drop or more localized deposition on tube sheet/tube entrance is expected to result in some local blockage and result in moderate impact on pressure drop.
2.	Higher importance in period 1 because there can be higher net flows through the reactor system which would cause more entrainment. a. High importance as intermittent steam flows are expected to be high contributing to steam binding phenomena. b. High importance as intermittent steam flows and hence intermittent entrainment is expected to be high. c. High importance when steam velocity is high; importance decreases with decay heat level.
3.	Low importance as steady liquid entrainment is expected to be small.

Table 8-10a Rankings for Cold Leg/Pump Region

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
1. Transport/mixing due to unsteady or oscillatory flow resulting from reactor vessel / loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping)	H		Same as Period 1a		Same as Period 1a		M		N/A	
a. Impact of coupling due to increased loop pressure drop due to high intermittent steam flow.	H	M					M	M	N/A	
b. Impact of condensation of steam due to contact with cold leg SI which changes the pressure in the cold leg and feeds back on the system stability.	H	M					M	M	N/A	
c. Impact of increasing the spillage out the break that changes the break pressure drop and feeds back on the system stability.	H	M					M	M	N/A	

Table 8-10a Rankings for Cold Leg/Pump Region (cont.)

Phenomena Description	Turbulent and Unsteady Reactor Vessel Flow Dominated Mixing Period						Transition Period		Convection Transport Dominated Period	
	Period 1a		Period 1b		Period 1c		Period 2		Period 3	
	Un-Buffered Boric Acid		Un-Buffered/ Buffered Boric Acid		Buffered Boric Acid					
	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK	Rank	SOK
d. Impact of transport of liquid to loop seal causing refilling and potential level depression in the inner reactor vessel and reducing liquid mixing volume in inner reactor vessel.	M	M	Same as Period 1a		Same as Period 1a		M	M		
e. Impact of cold leg/pump region hydraulic resistance, inertance, and capacitance on system stability.	H	M					M	L	N/A	
2. Transport and generation of turbulence associated with cold leg discharge into down comer as related to turbulent transport/mixing within reactor vessel.	L						N/A		N/A	
3. Transport and generation of secondary flow patterns within cold legs as related to mixing in reactor vessel.	L						N/A		N/A	

Table 8-10b	Rationale for Cold Leg/Pump Region
1.	Higher importance in period 1 because there can be higher net flows through the reactor system which would cause more uniform mixing. a. Higher importance early on as entrainment is higher due to higher gas velocity. Importance diminishes with time as decay heat hence, gas velocity, decreases. b. Higher importance early on as condensation is higher due to higher steam flow. Importance diminishes with time as decay heat hence, steam flow, decreases. c. Higher importance early on as pressure drop is higher due to higher gas velocity. Importance diminishes with time as decay heat hence, pressure drop, decreases. d. Moderate importance as refilling the loop seal piping could impact the core region liquid mixing volume due to mixture level depression; not ranked high as level swell phenomena are expected to be more important in determining two-phase mixture level. e. Higher importance early on as pressure drop is higher due to higher gas velocity. Importance diminishes with time as decay heat hence, pressure drop, decreases.
2.	Low importance as turbulence level is expected to be lower due to less complex geometry compared to lower plenum/core region.
3.	Low importance as convection and turbulence mechanisms in the lower plenum/core regions are expected to be more important.

8.4 SUMMARY OF HIGH RANKED MIXING AND TRANSPORT PHENOMENA

The PIRT process yielded several high-ranked phenomena important to boric acid mixing and transport within a reactor vessel following LOCAs. In summary those high-ranked phenomena included the following:

- Boric acid accumulation due to decay heat boil-off.
- Turbulent convection/dispersion of boric acid due to void motion within the core region.
- Natural convection mixing and transport of boric acid due to boric acid concentration gradient between the core region and other regions within the reactor vessel such as the barrel/baffle region, core support region, and lower head region.
- Turbulent mixing and transport throughout the reactor vessel.
- Transport of lower concentration boric acid liquid in excess of make-up for boil-off from downcomer to inner reactor vessel liquid mixing volume regions.
- Natural circulation transport of boric acid from upper plenum/core to downcomer via hot leg nozzle gap and/or RVVVs (B&W plants).
- Transport of boric acid due to circulation/communication between core, upper plenum and hot leg regions of liquid mixing volume.
- Natural circulation transport of boric acid within core region due to "chimney effect" of hot power channel.
- Transport/Mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects.

BULK ACCUMULATION OF SOLUTE IN LIQUID MIXING VOLUME DUE TO DECAY HEAT BOIL-OFF

Accumulation of solute in the liquid mixing volume occurs as a consequence of decay heat boil-off of the liquid inventory coupled with low miscibility in the vapor phase (i.e., steam). As a result, accumulation of solute due to decay heat boil-off is considered a high-ranked phenomenon throughout all phases of mixing and transport. It is the primary phenomenon by which solute concentrates in the liquid phase inventory in the reactor vessel.

Accumulation of solute due to stored energy related (from reactor vessel structures) boil-off was not considered to have a significant impact (relative to decay heat boil-off) on bulk accumulation especially in the later phases when stored energy has long been removed.

TURBULENT TRANSPORT/MIXING (CONVECTION/DISPERSION) DUE TO VOID MOTION WITHIN BOILING REGION OF CORE

Void (i.e., vapor) motion in the boiling region of the core is a phenomenon that causes turbulent agitation and mixing (i.e., dispersion) of the liquid inventory. The chaotic motion of the voids pushes and drags liquid as the voids circulate through the core region. The two-phase flow regime is considered to have a very important impact on the void motion phenomenon. For example, churn-turbulent two-phase flow regime in the core region would be expected to provide more effective vigorous void motion and therefore turbulent mixing of boric acid in the liquid inventory relative to the bubbly flow regime which is less turbulent.

As void motion significantly contributes to mixing and transport of boric acid within the core region of the liquid mixing volume, it is considered a high-ranked phenomenon throughout all phases of mixing and transport. Even though the two-phase flow pattern or veracity of boiling-induced void motion may change with decay heat level or safety system design or alignment, boiling and associated turbulent transport/mixing will always be present in the core region.

NATURAL CONVECTION TRANSPORT OF HIGHER CONCENTRATION SOLUTION FROM CORE REGION TO OTHER REGIONS WHERE CONCENTRATION IS LOWER SUCH AS CORE SUPPORT, BARREL/BAFFLE, AND LOWER HEAD REGIONS

Natural convection mixing and transport within the core region and between the core region and other regions is a high-ranked phenomenon for many phases of mixing and transport. Natural convection is a fluid density instability phenomenon driven by density gradients in the fluid. In the reactor vessel there are three primary driving mechanisms behind these density gradients that cause natural convection, namely, temperature, void fraction, and concentration gradients.

Convection associated with the temperature and void fraction gradients within the core region are high-ranked phenomena throughout all phases of boric acid mixing and transport as core decay heating is always present to establish a temperature or void fraction gradient. The temperature and void fraction gradients which increase from the core inlet toward the core exit region have the effect of causing the fluid density to decrease with elevation through the core region.

Convection associated with the concentration gradients between the core and other regions becomes more important as the concentration difference increases due to decay heat boil-off. Consequently, concentration-driven convection is a high-ranked phenomenon in the later phase of mixing and transport. The concentration gradient which increases from the lower regions of the reactor vessel toward the upper regions has the effect of increasing the fluid density with elevation in opposition to the temperature and void fraction gradient impact on fluid density.

TURBULENT MIXING (DISPERSION) AND TRANSPORT WITHIN NON-BOILING REGION OF CORE, CORE SUPPORT REGION, AND LOWER HEAD REGION

Turbulent mixing, or more specifically turbulent dispersion phenomena, occurs throughout the liquid mixing volume in the reactor vessel as turbulence is generated from flow across numerous complex hydraulic structures such as fuel assemblies and grids, core support plates, and lower internals structures.

Flow across these structures generates turbulence via flow separation, vortex shedding, and shear flow instability.

Another possible mechanism or route for turbulence generation is that associated with shear instability from convection phenomena. For instance, at low Rayleigh numbers, laminar rotating convection cells may be established. As Rayleigh number increases due to increase in density difference (due to concentration or temperature difference), chaotic convection cell patterns may occur. With further increase in Rayleigh number, the convection pattern may transition to turbulent pattern.

In the boiling region of the core, turbulence is also imparted to the liquid mixing volume due to chaotic boiling and void motion. It is expected that high turbulence intensity levels will result from boiling and void motion coupled with turbulence generated from flow across fuel assemblies and grids. Therefore turbulence is considered a high-ranked phenomenon in the core region during all phases of mixing and transport.

Turbulence is not considered a high-ranked phenomenon in other regions of the reactor vessel such as the core support region or lower head regions in the early phase, not because turbulence levels are insufficient for mixing, but rather there is not significant accumulation of solution until later phases when convection processes transport higher concentration solution from core region to regions such as the core support region and lower head regions. Consequently, as solution is transported from the core region to lower reactor vessel regions during later phases, turbulence becomes more important as it contributes to mixing and transport of boric acid within those regions.

TRANSPORT DUE TO CIRCULATION/COMMUNICATION BETWEEN CORE, UPPER PLENUM AND HOT LEG REGIONS OF LIQUID MIXING VOLUME

Higher concentration solution in the core region may be circulated (diluted) with the liquid volumes in the upper plenum and hot leg. The phenomena that allows this communication may be more direct via two-phase mixture level swell into upper plenum or hot leg regions. Or it may be indirect communication via liquid entrainment from the core region to the upper plenum/hot leg where liquid de-entrains, mixes with liquid mixing volume in those regions and liquid returns back toward core region.

NATURAL CIRCULATION TRANSPORT WITHIN CORE NON-BOILING REGION AND CORE SUPPORT REGION DUE TO "CHIMNEY EFFECT" OF HOT POWER CHANNEL

The "chimney effect" of the hot power channel produces natural circulation within the core and core support regions. The hot power channel increases local buoyancy of the fluid (relative to nearby fluid channels) and induces a secondary flow circulation pattern that enhances mixing. Although this "chimney effect" phenomenon may occur in the boiling region as well, it is not ranked as a separate phenomenon as in the non-boiling region of the core. Instead, it is included under turbulent transport/mixing associated with boiling and void motion since this phenomena dominates in the boiling region of the core.

TRANSPORT OF LOWER CONCENTRATION SOLUTION (IN EXCESS OF MAKE-UP FOR BOIL-OFF) FROM DOWNCOMER TO INNER REACTOR VESSEL LIQUID MIXING VOLUME REGIONS

As the concentration increases in the core support and lower head regions, the inflow of lower concentration solution to make up for core boil-off promotes a dilution effect in these regions. This phenomenon contributes to promoting density-driven convection from the core region toward the lower reactor vessel regions and contributes to maintaining/increasing liquid mixing volume.

NATURAL CIRCULATION TRANSPORT OF HIGHER CONCENTRATION SOLUTION FROM UPPER PLENUM/CORE TO DOWNCOMER VIA HOT LEG NOZZLE GAP AND/OR RVVVs (B&W PLANTS)

The transport of higher concentration solution out of the upper plenum/core regions after the mixture level in the reactor vessel reaches the hot leg and/or RVVV elevation is a high-ranked phenomenon as it contributes to dilution in the core region. This phenomenon is ranked high later in the transient as concentration increases in the upper plenum/core regions.

TRANSPORT/MIXING AND UNSTEADY LIQUID ENTRAINMENT DUE TO UNSTEADY OR OSCILLATORY FLOW RESULTING FROM REACTOR VESSEL/LOOP SYSTEM INTERACTION EFFECTS

Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects is high ranked for the early phase as intermittent steam velocities are expected to be at a maximum and enhance system interaction effects. The system interaction effects are driven by coupling of reactor vessel mixing regions (such as core, core support, barrel/baffle, and lower head regions) with other reactor coolant system regions such as the steam generators and loop piping. System interaction effects are expected to decrease in importance as decay heat levels decrease.

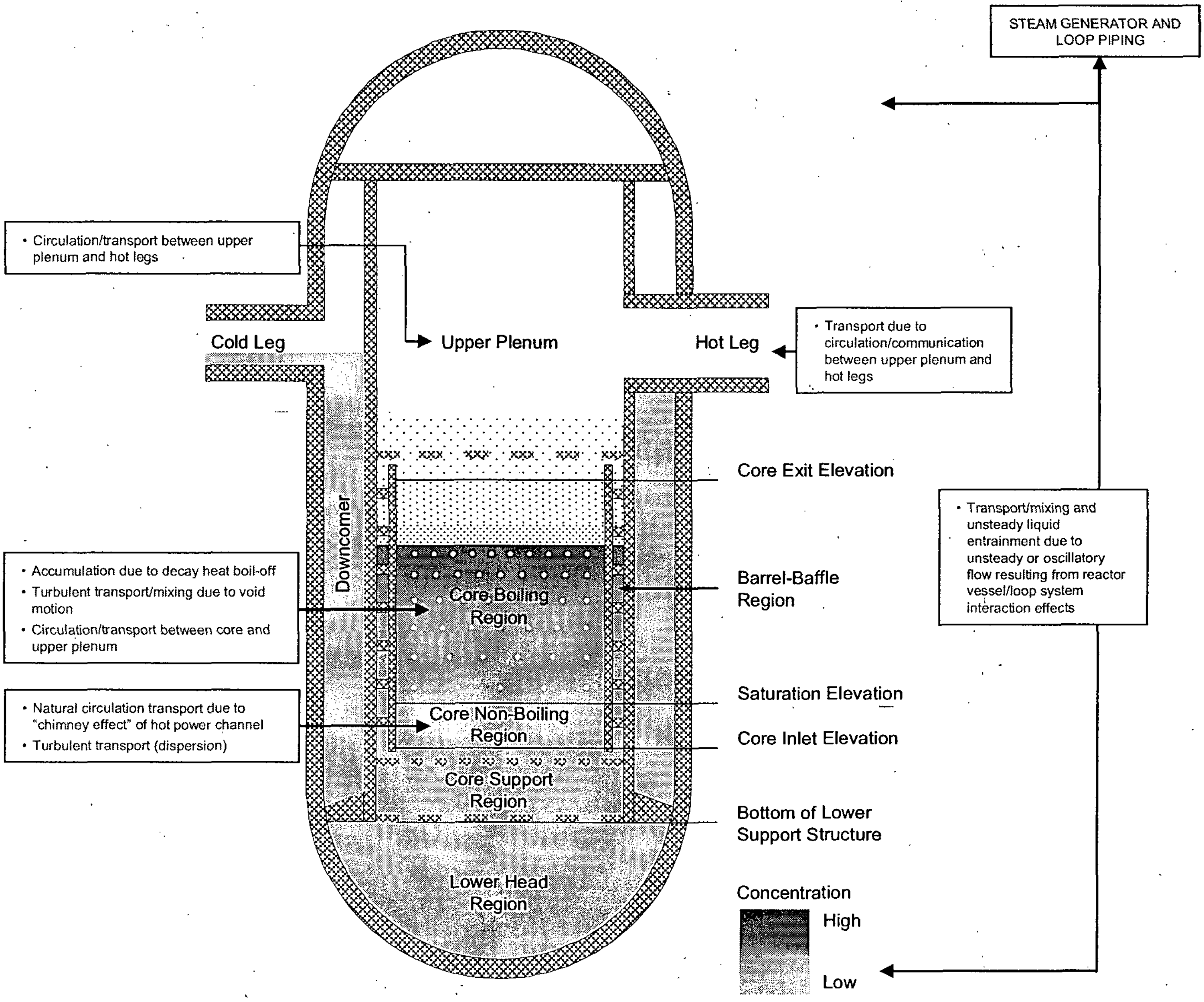

Figure 8-1 Expected Boric Acid Concentration Distribution and Summary of High-Ranked Phenomena During the Turbulent and Unsteady Reactor Vessel Flow Dominated Period

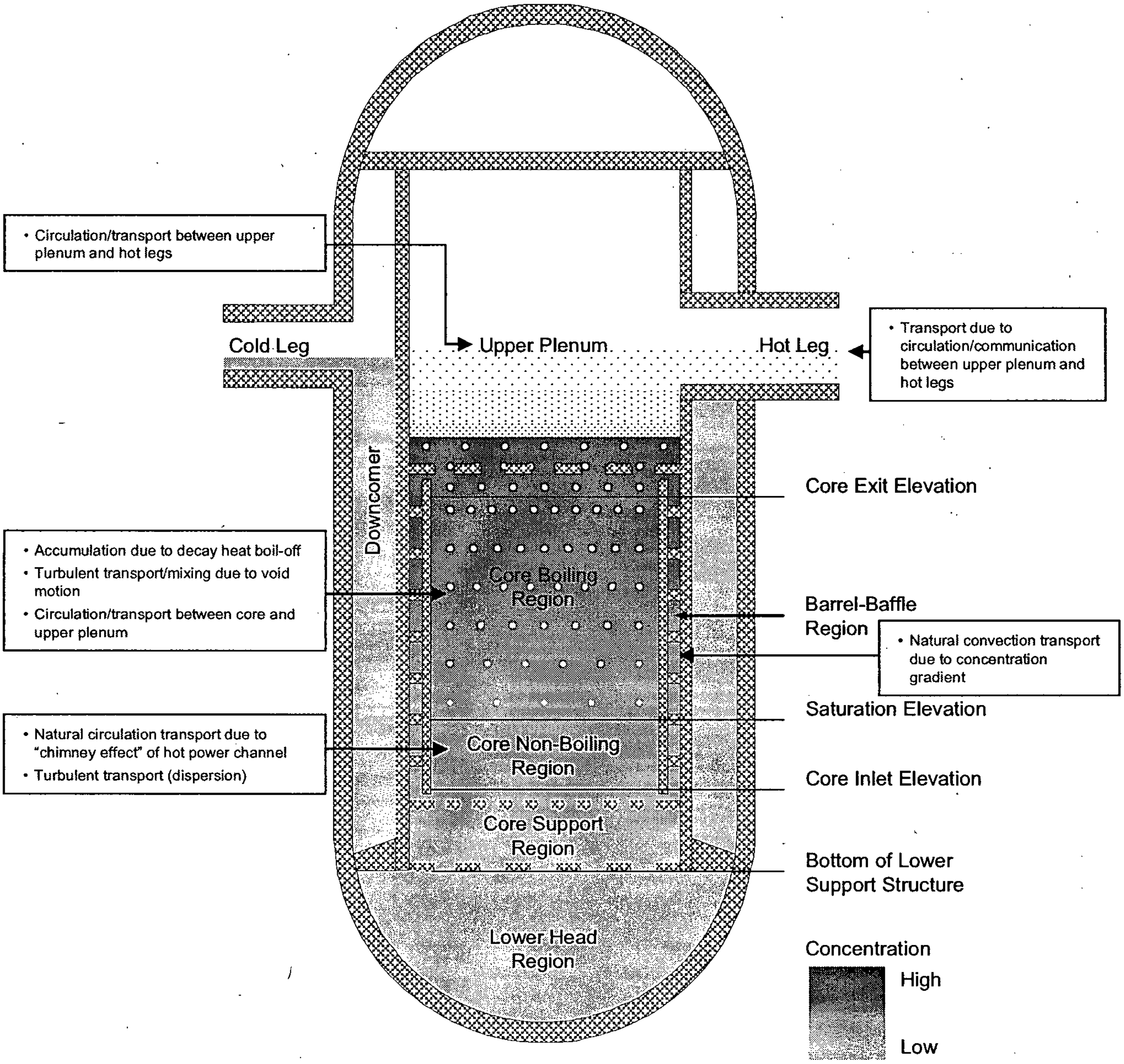

Figure 8-2 Expected Boric Acid Concentration Distribution and Summary of High-Ranked Phenomena During the Transition Period

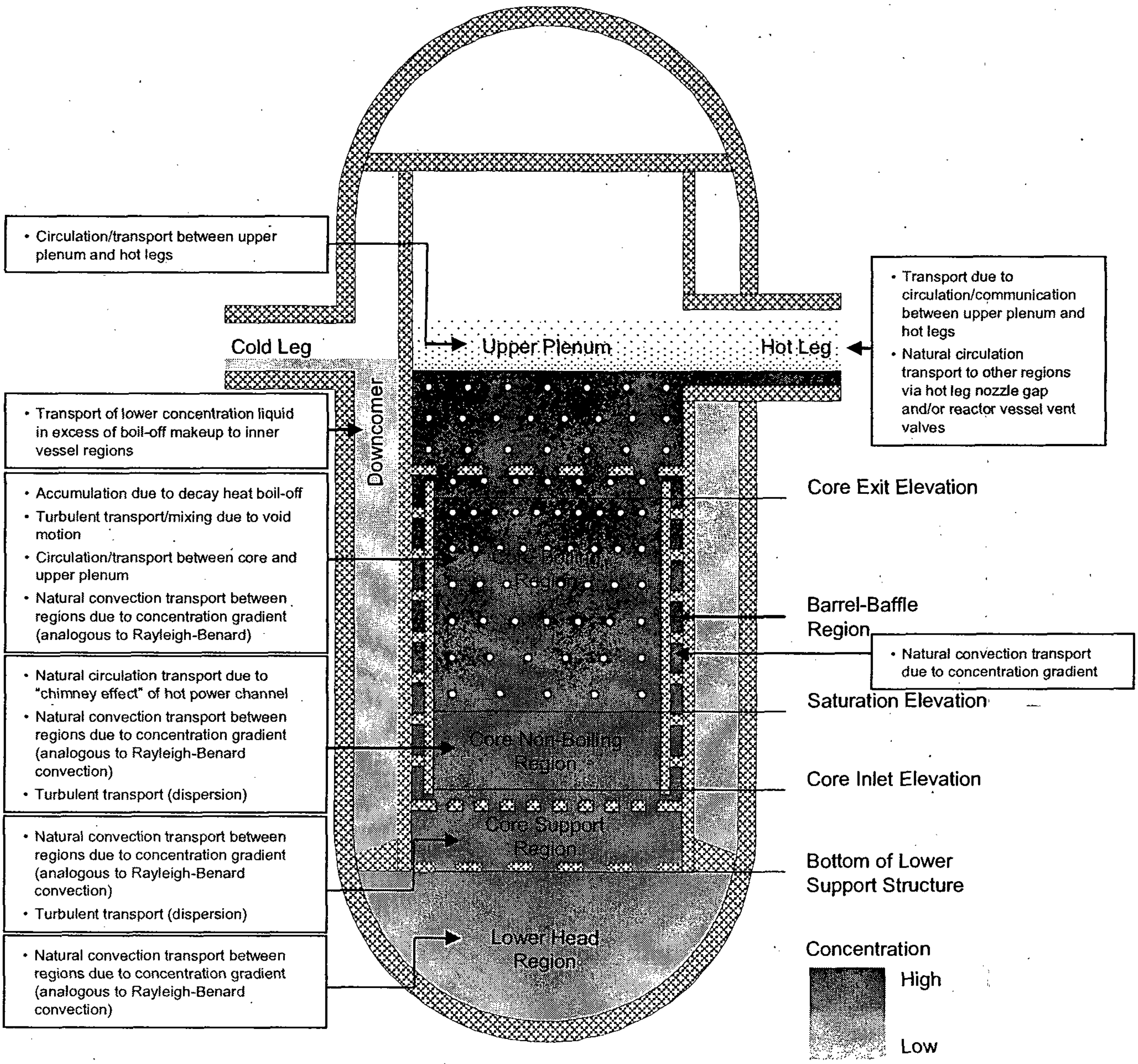

Figure 8-3 Expected Boric Acid Concentration Distribution and Summary of High-Ranked Phenomena During the Convection Transport Dominated Period

8.5 STATE OF KNOWLEDGE OF HIGH RANKED MIXING AND TRANSPORT PHENOMENA

The state of knowledge for mixing and transport is considered in general to be sufficient for purposes of identifying and ranking phenomena and hence produce a useful PIRT. The state of knowledge for some high-ranked phenomena for purposes of modeling and analysis of mixing and transport in a reactor vessel for post-LOCA conditions, however, is considered to be low. This is especially true for high-ranked acid mixing and transport phenomena related to unsteady system interaction effects and to natural convection driven by fluid density instability that is dependent upon concentration and temperature gradients and dependent upon the complex flow pattern/circulation and geometry of the reactor vessel. This points to the need for testing and supporting model development to improve the state of knowledge of this high-ranked phenomenon.

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9 IMPACT OF SUMP DEBRIS ON PIRT AND RANKINGS

The PWR Owners Group has funded a number of initiatives to address post-LOCA ECCS performance issues with regard to NRC Generic Safety Issue GSI-191 (Section 8, Reference 9) and the subsequent NRC Generic Letter 2004-02 (Section 8, Reference 10). Initiatives included the development of approaches to evaluate the downstream impact of sump debris, the development of approaches to evaluate chemical effects on the performance of ECCS systems, and alternate sump pH buffering agents (Section 8, References 11, 12 and 13). Most recently, the PWROG funded an initiative to develop an approach for evaluating sump debris and chemical effects on long-term cooling (Section 8, Reference 14). Insights gained from these initiatives underscore the potential for sump debris and chemical effects to impact precipitation modes and mixing/transport phenomena in the reactor vessel after a LOCA.

For low levels (i.e. level comparable to "normal impurities") of sump debris or chemistry effects it is expected that no new important phenomena would be introduced in the precipitation modes and mixing/transport PIRTs. It is expected that overall the mixing/transport phenomena may be degraded or altered somewhat for low levels of sump debris or chemistry effects but not to the point that would alter the relative ranking of the most important phenomena.

For moderate to high levels of sump debris or chemistry effects, it is plausible that new important precipitation modes may be introduced such as that due to chemical reactions that produce other precipitates. It is also plausible that for moderate to high levels of sump debris or chemistry effects, the ranking for some precipitation modes may change such as the following:

- The presence of moderate to high levels of sump debris or other chemical precipitates may increase the potential (and hence ranking) for heterogeneous nucleation and growth in the bulk solution.

- The formation of very small flow passages (i.e. porous media) due to sump debris bed formation may increase the potential for precipitation effects associated with confined fluid phenomena, particularly in the core region.

- Core blockage resulting from sump debris may increase precipitation associated with boiling/evaporating films and/or droplets on heated surfaces due to higher void fraction and increased liquid film/droplet production from associated two-phase flow regimes in the core region.

- Core blockage resulting from sump debris is also expected to reduce or restrict convective mixing/transport between core and lower reactor vessel regions, thereby further increasing the potential for precipitation to initiate in the upper reactor vessel regions (as describe above) and decreasing the potential for precipitation to initiate in the lower reactor vessel regions due restricted transport of higher concentration solution from the core region to the lower reactor vessel.

- Increased debris volume translates into reduced chemical solution mixing volume which increases the potential for bulk precipitation.

For moderate to high levels of sump debris or chemistry effects it is expected that overall important mixing/transport phenomena would further degrade and that it is possible that new mixing/transport phenomena may be introduced or at least that the relative ranking of phenomena may change due to alteration of flow pattern or regime include the following:

- The relative ranking between concentration-driven natural convection and double diffusive convection or possibly molecular diffusion on the impact of solute transport from the core region to the core support, barrel/baffle, or lower head regions may change as a result of increased debris-related hydraulic resistance.

- Increased sump debris level may clog or restrict flow through the hot leg nozzle gap significantly degrading the effectiveness of transport from the core/upper plenum to the down comer liquid volume via the hot leg nozzle gap.

- For turbulent transport/mixing of solute, sump debris may have some opposing effects. Collection of sump debris on reactor vessel structures/surfaces may enhance turbulence levels due to increased roughness or vortex shedding. On the other hand, additional sump debris or chemistry effects may increase the effective fluid viscosity such that turbulence levels are reduced and turbulent mixing is degraded. Similarly turbulent void motion and flow regime in the core region could be significantly impacted in the presence of higher levels of sump debris.

- Unsteady system interaction effects such as interaction between the reactor vessel and steam generator/loop piping may reduce the impact of sump debris on mixing/transport by altering reactor vessel flow patterns and/or altering distribution and packing of debris.

In summary, it is expected that the Precipitation Modes and Mixing/Transport PIRTs should be applicable for low levels of sump debris and chemistry effects. However, it should be recognized that the state of knowledge for some important phenomena is currently rather low and as sump debris levels or chemistry effects increase, the current PIRTs would need to be re-evaluated and likely modified.

10 OVERALL CONCLUSIONS FROM PRECIPITATION MODES AND MIXING/TRANSPORT PIRTS

Precipitation is most expected to initiate in the upper and/or lower reactor vessel regions consistent with available precipitation tests. Precipitation may occur in the steam generator region depending upon entrainment of solution to the steam generator region and whether the steam generator is acting as a heat sink or heat source. However, the current state of knowledge is very low with respect to steam generator related phenomena. Precipitation in the non-boiling region of the core, single phase region of the barrel/baffle, down comer and hot leg is not expected to initiate before other regions such as the lower head or core boiling regions.

<u>Phenomena Rankings</u>

Mixing/Transport and Precipitation in Lower Reactor Vessel Regions (Core Support and Lower Head Regions)

The high-ranked mixing/transport phenomena in the lower reactor vessel regions include natural convection (density driven convection due to concentration gradient) transport of higher concentration solution from the core region to the core support and lower head regions and include turbulent mixing within these regions associated with geometry and unsteady system interaction effects. Mixing/transport early in the post-LOCA period is expected to be driven largely by turbulent and unsteady system interaction effects whereas in the later post-LOCA period mixing/transport is expected to be driven largely by natural convection due to the concentration gradient in the reactor vessel.

Precipitation in the lower reactor vessel regions is expected to be driven by super-saturation, heterogeneous nucleation and growth on cool surfaces. Super-saturation in the lower reactor vessel regions results from the combination of "cold" safety injection and transport of higher concentration solute from the upper regions to the lower regions of the reactor vessel via natural convection. "Cold" surfaces result from cold leg injection heat transfer associated with flow past lower internals structures such as support columns, bottom-mounted instrumentation tubes, and flow skirts. Precipitation is most likely to be a crystalline form on solid structures with a relatively slow growth rate that is controlled by natural circulation transport from the core region and convection/turbulent mixing with incoming un-saturated, but, relatively "cold" buffered or un-buffered boric acid solution from the down-comer.

Mixing/Transport and Precipitation in Upper Reactor Vessel Regions (Core Boiling, Upper Plenum, and Two-Phase Barrel/Baffle Regions) and Steam Generator Region

The high-ranked mixing/transport phenomena in the upper reactor vessel regions where two-phase conditions exist include turbulent mixing due to void/bubble motion within these regions, natural convection transport due to concentration gradient, and transport due to entrainment, level swell, and unsteady system interaction effects. Entrainment is the high-ranked transport phenomena for the steam generator.

Precipitation in these regions is expected to be a result of high super-saturation associated with evaporation of liquid films/droplets on heated or boiling surfaces. Precipitation is expected to be of an amorphous form, particularly where boiling occurs, due to the high super-saturation and rapid evaporation on solid structures such as fuel rods, guide tubes, or steam generator tubes where thin films or droplets exist. Hot leg or upper plenum injection is expected to re-dissolve this type of precipitate in the upper reactor vessel regions.

Mixing/Transport and Precipitation in Non-Boiling Core Region of Reactor Vessel and Single Phase Barrel/Baffle Region

Mixing/transport phenomena in the core non-boiling region include natural circulation due to chimney effect, concentration driven natural convection, turbulent mixing and unsteady system interaction effects. Due to heating, particularly in the non-boiling region, the solubility of the solution is higher relative to lower reactor vessel regions. However, there is no evaporation/boiling in the non-boiling core or single-phase barrel/baffle regions to cause high super-saturation of the solution as in the core boiling region, and no cooling to super-saturate the solution as in the lower head region. Therefore, consistent with available tests, precipitation is not expected to initiate within the non-boiling core region and single-phase barrel/baffle regions.

Mixing/Transport and Precipitation on Hot Leg and Down-comer Regions

The high ranked mixing/transport phenomenon is the transport of high concentration solution via hot leg nozzle gap or reactor vessel vent valves (B&W plants) into the down comer region. Precipitation is not likely to initiate in the hot leg itself as there are no heated surfaces to cause super-saturation. Precipitation in the down comer is not expected to initiate before other regions as only small quantities of high concentration boric acid solution are expected to be transported into the large volume of low concentration solution stored in the down comer.

Phenomena State of Knowledge

PIRT rankings of precipitation modes and mixing/transport phenomena show that in addition to global phenomena, local/regional phenomena can be of high importance as well, particularly for expected precipitation modes. However, there is generally a low state of knowledge about local/regional level phenomena of buffered/un-buffered boric acid solution in reactor vessel geometry. To improve this state of knowledge and to support predictive models that may be applied in boric acid precipitation methodology, it is recommended that future testing include local/regional level measurements and data.

11 RECOMMENDATIONS

Based upon the results of the PIRT development process, the following recommendations are made for addressing buffered/un-buffered boric acid precipitation modes and mixing/transport issues:

- Using the current PIRTs as a basis, develop PIRTs to address buffered/un-buffered boric acid mixing/transport under various levels of sump debris or chemical effects.
- Using the results obtained from the precipitation modes and mixing/transport PIRTs and what may be available from the open literature, develop "first principles" type model(s) that address the high-ranked phenomena. The model(s) will serve to contribute to the state of knowledge and to provide a basis to support scaled testing and plant evaluation model development work.
- Plan and execute scaled testing to improve the state of knowledge of buffered/un-buffered boric acid precipitation modes and mixing/transport phenomena and to support models development. Improved state of knowledge and models are prudent for addressing NRC issues.
- Testing and supporting model development should focus upon high-ranked phenomena including the following:
  - Natural convection driven by concentration gradient as related to solute mixing and transport within the complex geometry of the reactor vessel.
  - Precipitation on cooled surfaces in lower reactor vessel regions such as the lower head internals structures.
  - Precipitation on heated/evaporating/boiling surfaces in upper reactor vessel regions such as on fuel rods in the core and on steam generator tubes.
  - Entrainment and high void, two-phase flow regime behavior in upper reactor vessel regions and steam generator.